# COMPOST QUALITY RECOMMENDATIONS FOR REMEDIATING URBAN SOILS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

Hannah Heyman

August 2019

ABSTRACT

Poor soil health is a critical problem in many urban landscapes. Degraded soil restricts plant growth and microorganism activity, limiting the ability of urban landscapes to perform much needed ecosystem services. Amending soil with compost can increase infiltration, microbial biomass, cation exchange capacity, available water holding capacity, and structural stability. Incorporation of approximately 33% compost by volume into degraded soil has been proven to improve soil health and structure over time while avoiding the financial and environmental costs of importing soil mixes. However, additions of high volumes of compost could potentially increase the risk of nutrient loss through leaching and runoff. The objective of our study was to consider the effects of different compost amendments on soil health, plant health and susceptibility to nutrient leaching.

We conducted a bioassay to measure the effect of composts made from different feedstocks on various plant health characteristics. We also collected leachate during the experiment to measure nutrient loss from our different compost-amended soils. We found that all compost amendments improved soil health. Nutrient-rich, manure-based composts produced greater plant growth, but those composts also leached higher concentrations of nitrate and phosphorus. We found composts made from of leafy green waste and food scraps provided sufficient nutrients for plant growth without excess nutrient loss. Using our findings along with those found in the literature, we provided ranges of compost characteristics to inform the selection of compost for on-site soil remediation. Additionally we concluded, careful consideration of soil texture and an understanding of the conditions and limitations of the intended remediation site are vital in achieving optimal results.

# BIOGRAPHICAL SKETCH

Hannah “Compost Queen” Heyman was born in Hartsdale, NY. She came to Cornell University after several years working in a variety of positions that covered environmental education, botanical field research, small-scale commercial farming and public horticulture. Hannah received her B.S. from the University of Michigan in 2014 with a major in Environmental Science. She has certifications in permaculture design and as a Master Composter. Her hobbies include baking, yoga, ultimate frisbee and spontaneous singing. Throughout her education and early career, Hannah has been motivated by her belief in advocating for environmental stewardship and responsible land management and she hopes to continue in that vein in her future career.

For my parents, Fran and Dan Heyman. Thank you for everything.

# ACKNOWLEDGMENTS

There are many people I would like to thank. First and foremost, I would like to thank my advisor, Dr. Nina Bassuk, for providing me with this incredible opportunity and for her patience, guidance and invaluable wisdom. With a balance of practicality and humor she provided an atmosphere where I could ask questions, push myself and develop as a scientist. I would also like to thank my committee members, Jean Bonhotal and Dr. Todd Walter, for providing their precious time, insight and support. I would like to thank Tommi Schieder for all her assistance in the lab, her enthusiasm and dependability. I would also like to thank my peers in the field of Horticulture who helped me with my research and with learning the ropes in a new academic community, particularly Dr. Grant Thompson and Brandon Miller, for their advice, encouragement and generosity.  I would also like to thank my family and friends for their boundless support and love.

TABLE OF CONTENTS

**ABSTRACT** ........ i

**BIOGRAPHICAL SKETCH** ........ iii

**ACKNOWLEDGMENTS** ........ v

**TABLE OF CONTENTS** ........ vi

**LIST OF FIGURES** ........ vii

**LIST OF TABLES** ........ viii

**CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW** ........ 1

Introduction ........ 1

What is Compost? ........ 2

Feedstocks ........ 2

Methods of Composting ........ 5

The Composting Process ........ 7

Compost Quality ........ 9

Specifications ........ 20

Benefits of Compost as a Soil Amendment ........ 22

Drawbacks ........ 26

Places for Growth in the Composting Industry ........ 28

Conclusion ........ 30

References ........ 31

**CHAPTER 2: COMPOST QUALITY RECOMMENDATIONS FOR REMEDIATING URBAN SOILS** ........ 41

Abstract ........ 41

Introduction ........ 42

Methods ........ 44

Results ........ 52

Discussion ........ 69

Conclusion ........ 80

References ........ 81

Appendix A ........ 86

**Appendix B:** Scoop and Dump Compost Specification (For planting beds) ........ 87

LIST OF FIGURES

Figure 1. Composition of the compost particle size .................................................................... 55

Figure 2. Relationship between dry shoot weight of the bean plants and Carbon to Nitrogen ratio ........................................................................................................................................ 57

Figure 3. Relationship between dry shoot weight of the bean plants and soluble salts concentration of the amended and unamended soil ..................................................................... 58

Figure 4. Relationship between extractable (available) phosphorus content of the 33% and 50% amended soil and control treatments and bean dry shoot weight. ............................................... 59

Figure 5. Relationship between dry shoot weight of the bean plants and OM% of the growing media.......................................................................................................................................... 60

Figure 6. Mean bean plant dry shoot weight in grams by compost type ..................................... 61

Figure 7. Mean bean plant leaf area in $cm^2$ by compost type. .................................................... 62

Figure 8. Mean bean leaf SPAD (greenness) by compost type. ....**Error! Bookmark not defined.**

Figure 9. Relationship between extractable (available) phosphorus content of the amended and unamended soil with concentration of soluble phosphorus found in leachate............................. 65

Figure 10. Relationship between nitrate concentration in the composts alone............................ 66

Figure 11. Mean soluble phosphorous found in leachate by compost type. ................................ 67

Figure 12. Mean soluble Nitrate found in leachate by compost type .......................................... 68

## LIST OF TABLES

Table 1. Seventeen composts collected from around New York State ........................................ 45

Table 2. Compost characteristics ........................................................................................ 46

Table 3. Unamended and amended soil characteristics. .............................................................. 54

# CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

## Introduction

Composting is a sustainable, rapidly expanding waste management strategy and compost, the renewable, upcycled, product, has many important uses in the landscape industry. In the industry today, however, compost is immensely underutilized, and its production process and quality control are not well understood. There are a myriad of parameters with which to assess compost quality, some being baseline criteria, intended to protect consumers from contamination or other detrimental impacts of poorly managed compost. Whereas other parameters are aspects of compost quality that are specific to its different end use applications (Tognetti et al. 2011).

In this review we will examine the many variants of compost and composting methods commonly used and we will evaluate the definition of compost quality as it applies to its use as a soil amendment. Compost has been shown to improve physical, biological and chemical properties of many types of soil. It can increase porosity, organic-matter content, microbial biomass, available water holding capacity, and structural stability (Mikhailova et al. 2015). However, compost is highly variable. In order to reap the full benefits of soil remediation with compost, one must fully understand the qualities of the compost being used and the desired outcome of its application.

Compost characteristics are derived from its constitutional ingredients, the method with which it is made and the length of time it is given for decomposition and curing. Compost end users must better understand everything that goes into the finished product and clearly communicate their needs to producers. Those producers, too, must adjust their mindset of waste management to one of product manufacturing. If this shift is made the composting industry can become an effective, profitable, closed circuit system benefitting growers and compost producers alike.

**What is Compost?**

Compost is a broad term that can be defined as the product resulting from the controlled biological decomposition of organic materials, occurring under aerobic conditions with adequate moisture and temperature, sanitized through heat generation and stabilized to the point that it is appropriate for its particular application. Composting is the combination of the metabolic processes of many different microorganisms. The composting process mimics the natural processes of humification and nutrient mineralization. The resulting product is stable, but contains less carbon and nitrogen than its contributing parts (Alexander 2003; Azim et al. 2007; Roman et al. 2015; Zmora-Nahum et al. 2007). A major goal of composting for use in the landscape, is the removal of dangerous pathogens, which are killed during the thermophilic (highest temperature) phase, if it is maintained for an adequate period of time (Bollen et al. 1989; Termorshuizen et al. 2005). Compost can be made from nearly any organic material, meaning anything composed of carbon-based compounds found in nature.

**Feedstocks**

The specific material that compost is made from is called its feedstock. Because compost can be made from nearly any organic material, it is very difficult to regulate and standardize analytical testing. There are a handful of common categories of feedstocks used in commercial compost production such as agricultural byproducts, yard waste or green waste, biosolids (sewage sludge), food scraps (pre- and post-consumer), industrial byproducts, and municipal solid waste. Biosolids and many manures are often blended with a bulking material like wood chips, sawdust or paper to facilitate the composting process. The most common feedstocks used by compost producers in the United States are agricultural byproducts, yard waste and biosolids.

The category of agricultural byproducts covers a wide range of organic material such as manure and bedding from a variety of animals, animal carcasses, crop residues, unsold or unsellable fruits and vegetables, and byproducts from processing and packaging. Composts produced from agricultural byproducts, especially manures, are known for generally possessing higher nutrient concentrations and elevated salinity levels (USCC 2001).

All manure is not alike. An analysis of compost quality conducted by Jean Bonhotal et al. in 2008 showed that manure type was the only aspect of the composting process that had a significant effect on the resulting phosphorus levels, pH, soluble salt content, and bulk density of the finished compost product. Manure from ruminants (e.g. cattle and sheep) differs from manure from non-ruminants (e.g. pigs and poultry). Ruminants' digestive process produces manure with a nutrient ratio comparable with the nutrient ratio of the crops the ruminants eat.

Non-ruminants produce more nutrient-rich manure. Alsanius et al. (2016) conducted experiments where chicken manure was composted together with a carbon-rich feedstock (42.5 vol% bark), which resulted in what was considered a high-quality compost in terms of stability, organic matter (OM) content, carbon to phosphorus ratio and carbon to nitrogen (C:N) ratio. Composting chicken manure without a bulking agent, lead to severe nitrogen leaching (as much as 58% of the initial nitrogen). Poultry manure generally exhibited rapid nitrogen mineralization and little effective OM, so it was better used as a plant fertilizer than as a soil conditioner (Alsanius et al. 2016). Mixing nutrient-rich manure with carbon-rich bulking agents can provide compost with active biomass, increased surface area for oxygen transport during the composting process and can curb some of the nutrient leaching that will take place when composting manure on its own (Wang et al. 2004; Zmora-Nahum et al. 2007).

Green waste as a feedstock can consist of grass clippings, leaves, weeds, twigs, brush, woody debris, as well as any other vegetative material from land clearing activities. Green waste composts are typically lower in nutrients and contaminants. The soluble salt concentration in green waste compost is usually low as well, except in cases where the feedstock is collected from areas where road salts are used regularly (USCC 2001; Zmora-Nahum et al. 2007).

The main components of green waste compost are cellulose and lignin. Cellulose is the main source of energy that drives the biological transformations, temperature rise and chemical changes that occur during the composting process. Lignin is the starting material for the formation of humus. Lignin is the OM that is most difficult to degrade and that provides the water-holding, ion exchange, and bulking capabilities that improve soil health and productivity. During the composting process lignocellulosic materials increase air permeability and water retention (Hubbe et al. 2010). Tognetti et al. (2007) found shredding woody feedstocks initially leads to a more stable and mature product and that adding wood shavings increases OM and decreases pH, nitrate, extractable phosphorus and electrical conductivity.

Biosolids (sewage sludge) are the organic solid residue left over after wastewater processing and are generally very rich in nutrients. Biosolids are treated to reduce pathogens and generally contain only minimal levels of heavy metals and organic contaminants. Biosolids must meet a “Class A grade” by the EPA in the United States to obtain a permit for general distribution. Cogger et al. (2005) noted that biosolids composts contain greater amounts of phosphorous (P), but less potassium (K) than green waste composts. Chen et al. (1996) found similar amounts of P in composted cow manure and biosolids composts, but the cow manure compost contained significantly more K than biosolids compost.

Diverting food scraps from the landfill is increasing in popularity and many states in the U.S. are now passing laws to require or incentivize it, but it is still only a small percentage of the composting industry (Levis et al. 2010; Walker et al. 2006). Composts produced from food scraps are typically rich in nutrients and may also possess elevated salinity levels.

Traditionally, composts are made of a combination of manure and plant residues. Manure provides many nutrients, including N, P and K as well as an abundance of microorganisms, which enable a faster decomposition process. The plant material enables air penetration to all parts of the compost pile. Feedstocks, along with the compost management process, determine the humus content of the final product and the composition of the microbial population (Alsanius et al. 2016, Fierer 2017).

Regulatory organizations and non-profits, like the Organic Materials Review Institute (OMRI), provide municipalities with lists of accepted feedstocks for composting. The National Organic Program (NOP) is a regulatory program housed within the USDA Agricultural Marketing Service (ATTRA). Additionally, the United States Composting Council (USCC) published their Test Methods for the Examination of Composting and Compost (TMECC) which provides protocols for the composting industry to verify quality from feedstock collection to the end-product.

**Methods of Composting**

There are several critical variables to consider when creating compost, the C:N ratio of your inputs, particle size, moisture levels, pH, aeration, temperature, and time. The NOP provides time and temperature guidelines for compost producers. They recommend an initial C:N ratio between 25:1 and 40:1. For in-vessel or static aerated piles, compost should maintain a temperature between 131°F (55°C) and 170°F (77°C) for at least three days. However, for windrow systems, those temperatures must be maintained for 15 days and the pile must be turned a minimum of five times within that time period. The NOP also requires that accurate temperature records be kept throughout the entire process and, as previously mentioned, that only their listed acceptable feedstocks are used.

The composting process, at a basic level, is the oxidation of biomass with the production of carbon dioxide and heat, where cellulose and hemicellulose are the main carbon (C) sources (Dickson et al. 1991). These oxidation reactions require proteins and enzymes to take place, which means nitrogen is required in the mixture for the reactions to occur (Hubbe et al., 2010). Delgado-Rodriguez et al. (2010) found that nitrogen volatilization was reduced when the compost mixture had relatively high aeration, a C:N ratio of 60-70, and a moisture content greater than 55%.

Dougherty (1998) separated composting methods into four categories, open static piles, turned windrows (elongated piles that can be turned by tractors), aerated static piles, and in-vessel systems. The three non-static composting techniques all incorporate different strategies for overcoming certain drawbacks of the static pile, including uneven temperatures, uniform channeling of air, and the threat of accidental anaerobic zones within the pile (Alsanius et al., 2016).

In aerated static piles, air is forced through the pile either by blowing (positive pressure) or by drawing (negative pressure). Forced aeration has been shown to shorten the decomposition period from 40 days or more in the windrow system to about 21 days in the static pile system. The Beltsville system utilizes negative pressure, drawing air into the pile. The drawbacks of this system are cooling of the outside of the pile, and very high temperatures (>80°C) in the core of the pile. A positive pressure (blowing) method, developed at Rutgers University, met the oxygen requirements and created improved temperature conditions (Alsanius et al., 2016). In-vessel composting designs often involve the OM being conveyed continually through a long chamber. The composting process is relatively short in closed systems. However, it must be followed by a curing period to obtain adequate maturity (Alsanius et al. 2016; Hubbe et al. 2010).

Management and storage systems can significantly influence the quality of the finished product. Closed or indoor systems with manure-based composts show very high soluble salt levels. Protecting windrows from rainfall prevents leaching and results in a buildup of salts. Bonhotal et al. (2008) found that separation (separated solids and liquids vs. unseparated dairy manure) and pad type (soil, gravel or concrete) had an impact on several compost quality parameters. Separated manure had a significantly higher N content than unseparated manure. Pad type impacted N, P and OM content. Composts made on concrete pads had the greatest amount of N and OM, followed by gravel and then soil. Composts with the highest phosphorous content were made on soil pads. Bonhotal et al. (2008) suggested that the lower OM found in piles on soil and gravel pads might be due to dilution of the piles during the turning process. Soil and gravel can be easily scraped up by equipment and mixed into the windrow.

**The Composting Process**

The composting process can be divided into different phases characterized by temperature and in terms of the kinds of bacterial and fungal populations that thrive in different temperature ranges. These phases are the mesophilic (21-48°C), and thermophilic (45-68°C), the cooling phase and the curing or maturation phase. The mesophilic phase is when most of the breakdown of biomaterials occurs (Dickson et al. 1991). The pH decreases due to the organic acids released from the carbohydrates and lipids degraded by microorganisms (Tuomela 2000; Azim et al. 2018). Starting at around 40°C, mesophilic microorganisms are gradually replaced by thermophilic microorganisms. In the thermophilic phase detoxification and the breakdown of seeds takes place (Hubbe et al., 2010). In the cooling phase microbial activity slows and polymerization and condensation occurs and stable humus begins to form (El Fels et al. 2014). During maturation or curing, nitrogen should be mostly resistant to microbial degradation because of its incorporation into humic acid compounds (Roman et al. 2015; Azim et al., 2018).

Hoitink (1998) found that a water content of at least 35% was necessary for proper decomposition. Below 35% the bacteria in the compost did not have adequate moisture to grow a biofilm on the surface of compost particles. If the compost pile gets too dry, it will be difficult to re-wet the particles because hydrophobic fungi will have infected the compost particles (Sæbø and Ferrini 2006).

Research reviewed by Neklyudov et al. (2008) revealed a correlation between the quality of the compost and the array of microorganisms involved in the composting process. The bacteria and fungi associated with composting produce cellulolytic enzymes (enzymes that break down cellulose, e.g. cellulase). Several types of enzymes work in concert to effectively breakdown plant material.  Cellulose alone requires three types of enzymes for its decomposition, endocellulases, exocellulases and beta-glusocidases (Hubbe et al., 2010).

Different communities of bacteria, fungi, and protozoa are involved in the composting process at varying concentrations depending on the temperature, moisture content and the nature of the organic materials (Azim et al. 2018).

Nitrogen loss is a concern during the composting process, but Bueno et al. (2008) found that the use of a longer composting time, smaller particle size, a moderate moisture content (around 40%) and medium to lower aeration levels can mitigate this problem. Higher pH also tends to encourage the conversion of ammonium to the more volatile ammonia so extremely alkaline materials should be avoided for feedstocks (Dickson et al. 1991; Hubbe et al., 2010).

**Compost Quality**

Compost quality is not easy to standardize or succinctly define. There are many parameters to measure compost quality including age, maturity, stability, nutrient content, electrical conductivity, physical structure and contamination from pesticides, heavy metals or microbiological or biochemical sources. Naturally, all these properties vary widely by the feedstock source. Quality, however, cannot be judged on these characteristics alone. For compost to have utility, it must interact with an ecological system, therefore, compost quality is dictated by its end use (Emino and Warman, 2004).

The U.S. Composting Council provides guidelines for density, organic matter content, pH, soluble salts, maturity and several metals for multiple compost uses (USCC, 2001; Bonhotal et al., 2008). More specific parameters cited in the literature are C:N ratio, microbial activity, germination index, cation exchange capacity (CEC), humic substances content, weed seed content and ratios of ammonium and nitrate (Azim et al. 2018; Brinton, 2000).

Some compost quality parameters are indicators of safety, such as contamination and maturity. Those precautionary criteria, as well as things like smell and presence of inert particles (trash), apply to all compost regardless of their eventual use. Once those precautionary criteria are met, focus shifts to a second group of criteria related to the compost's end use as a soil amendment or plant growth promoter. Bioassays, using ryegrass, for example, are often utilized either to indicate nutrient release capacity or potential phytotoxicity (Rynk 2003; Tognetti et al. 2011).

Wood's End Research Laboratory's recommended values for finished compost as a plant substrate include soluble salt content (<2mmhos/cm), available N (100-300 mg/l), phosphate (800-2500 mg/l), potassium (500-2000 mg/l), maturity (Solvita 7-8), OM (>30%), pH (6-7) and foreign matter (<1% >2mm) (Brinton 2000).

In order to enable stakeholders to judge overall compost quality in India, Saha et al. (2010) came up with an indexing method for the categorization of composts into different marketable classes (A, B, C, and D) based on the values of total organic C, N, P, K, C:N ratio and respiration activity. The values of total C, N, P, and K that receive the highest scores in the index are >20% C, >1.25% N, >0.60% P, >1.0% K (dry matter). The values for C:N and respiration activity that receive the highest score are <10.1 and <2.1mg $CO_2$-C/g VS d, respectively. These values do not consider nutrient loss potential. Saha et al. believed grading of compost was required for stakeholders because of a lack of uniform feedstock composition and composting techniques. The purpose of the index was to help end users classify composts for use in different application areas (e.g. high value crop production, food crop production, fiber/flowering crop production, lawn/garden establishment, reclamation/rehabilitation of degraded lands) (Saha et al. 2010).

Bonhotal et al. (2008) conducted an end user survey, which revealed that growers were most interested in seeing pH, N-P-K content, OM and C:N ratio listed on a compost product label and were most concerned with weed seed, heavy metals and pathogen contamination. We will further discuss maturity, OM, C:N ratio, electrical conductivity, cation exchange capacity, particle size, N-P-K and contamination.

*Maturity*

Stability and maturity are two important and often interconnected aspects of compost quality. The stability of compost is measured by the degree of degradation of the organic material. Maturity, on the other hand, is defined by the amount or absence of damage to plants due to the use of the compost. The use of immature compost as a soil amendment will have negative effects on germination, growth and development of plants. Just because compost is stable, does not mean it is mature (Bernal et al. 1998; Castaldi et al. 2005).

The protocol for measuring maturity has proved to be a particularly difficult one for the academic community to agree on. Various studies on compost maturity use pH, C:N ratio, OM content, humification ratio or cation exchange capacity (CEC) as indicators (Albrecht 2008; Azim et al. 2018). Iglesias-Jiménez and Pérez-García (1991) stated that a C:N ratio of 15-20 characterizes mature composts. While Namkoong et al. (1999) asserted that a ratio of 10-15 can be considered stable although it depended on the initial materials used (Azim et al. 2018).

Cellulase activity is occasionally used as an indicator of maturity. Mature, finished compost should have a low cellulase content since the majority of the cellulose should broken down during the composting process. Smith and Hughes (2001) found the cellulolytic activity of twenty-eight visually mature composts ranged between 1.8% and 63.5% cellulose degraded, with an average of 25.2%. They conducted a bioassay with cress and found composts with high cellulolytic activity negatively affected root growth. They concluded that their method would need to be applied to a wider range of visually mature composts to determine a threshold value for cellulose degradation below which a compost can be considered mature and stable (Smith & Hughes 2001).

Albrecht et al. (2008) stated that humic acid content and the ratio of humic acids (HA) to fulvic acids (FA) are reliable measures of maturity, unlike the C:N ratio, which tends to decrease dramatically during the early phases of composting. In their study after doing chemical analysis on samples from 44 compost windrows, they found the average HA/FA ratio tripled from 0.5 to 1.6 over a period 142 days. C:N ratios decreased from 17.7 to 14.1 after 57 days and continued to decrease more gradually to 12.4 after 146 days (Albrecht et al. 2008). Nitrate content in compost has also been used as a maturity indicator. Microorganisms in compost decrease the ammonium content ($NH_4^+$) by converting it to nitrate ($NO_3^-$). Therefore, a higher concentration ratio of $NO_3^-$: $NH_4^+$ would indicate greater maturity (Albrecht 2007).

The Solvita® maturity test is based on the mineralization of C combined with the volatilization of ammonia (Woods Research® Management, USA). The compost moisture level must be adjusted to a level corresponding to the optimal microbial activity for the test to be performed. The Solvita® test is a unified system that estimates respiration and ammonia by a color forming chemical reaction and provides an interpretative table to assign the compost a grade from 1-8. A score greater than 5 indicates maturity, greater than 7 is deemed 'Very Mature' (Brinton and Evans 2000; Brinton 2000). Goyal et al. (2005) and Boulter-Bitzer et al. (2006) suggested that a combination of different parameters would be best for understanding maturity. Albrecht et al. (2009), similarly, proposed using an Overall Index of Composting

Development (OICD) that considers fourteen different physical and chemical parameters using the PCA (principal component analysis).

*Organic Matter*

Organic matter (OM) is a dynamic part of the C cycle in the soil. OM is defined as the sum of all organic components in soil including undecayed and partially decomposed plant and animal tissues as well as all soil biomass excluding macrofauna and macroflora (Vaughan et al., 1985). OM consists of non-humic and humic substances. Non-humic substances are easily degraded by soil organisms and include simple compounds (e.g. carbohydrates, aliphatic and aromatic hydrocarbons, amino acids, ethylene, hydrogen sulfide etc.). The humic portion of OM is made up of more complex molecules that are generally resistant to complete degradation. The two main components of humic substances are humic and fulvic acids (Thompson et al. 2002). Presence of humic substances have been proven to increase the cation exchange capacity (CEC) and the available water holding capacity (AWHC) in the soil. Many of the benefits associated with compost rely on the OM component reaching a sufficient level of stability. For erosion control, bioremediation of contaminated soils, and reestablishment of wetlands, a high degree of compost stability is essential for effective remediation (Zaccheo et al. 2002).

Khater (2015) conducted an experiment to study the physical and chemical properties of compost made with different proportions of a variety of feedstocks. The experiment revealed an inverse relationship between soil OM and soil bulk density. Soil bulk density decreased from 655 to 420 kg $m^{-3}$ when the total OM increased from 28.6 to 41.2%. Sax et al. (2017) found similar results. Hudson (1994) showed that the incorporation of OM into mineral soils decreased bulk density between 1 and 6% when OM made up 5–25% of the total volume of the experimental soil mixes. Soil OM in a range of 0.5% to 8.0% has been proven to increase AWHC in silt loam soils (Saxton and Rawls, 2006). Christenson (1986) found a direct correlation between total OM and aggregate stability.

OM can store nitrogen, phosphorus, and sulfur as well as supply those nutrients to plants for growth and development (Thompson et al. 2002). Brown et al. (2012) found that incorporation of OM into soils increased C content by 24% after a period of 2–15 years. Chen et al. (2013) found that compost incorporated deep into the soil profile increased total organic carbon (TOC) and microbial biomass C at depths of 15–30 cm. They inferred that the depth of incorporation could have possibly protected the OM from oxidation and microbial degradation. These results indicate that incorporation of OM into soils could increase their ability to sequester organic C. Composts that contain higher levels of stabile OM would therefore be considered higher quality for use as a soil amendment.

*C:N Ratio*

The proportion of carbon to nitrogen is particularly important when considering different compost uses. Carbon serves as a source of energy and an elemental component for microorganisms and nitrogen is essential for the synthesis of amino acids, proteins and nucleic acids. During the active phases of aerobic fermentation, the microorganisms consume 15 to 30 times more C than N (Mustin 1987). Wood-based composts take a longer time to mature (around 18 months) than a compost made with household waste with a lower C:N ratio (around 7 months) because of the recalcitrant C in wood, which is difficult to degrade (Azim et al. 2018).

De Bertoldi et al. (1983) conducted experiments on green waste compost either mixed with treated sewage sludge or not. In that study, they found that the optimal value of C:N ratio was 25, in the starting material. According to Sullivan and Miller (2001), ideal compost feedstock mixtures should have an initial C:N ratio of about 30:1, decreasing to less than 20:1 during the composting process. Higher C:N values slowed the rate of decomposition while lower values increased nitrogen losses.

According to Sikora and Schmidt (2001) the C:N ratio considered optimal for compost is based on the C:N ratio of stable soil OM which generally falls between 10 and 15. Chatterjee et al. 2013 stated in their review that the ideal ratio for a compost used as a growing medium was 12–18 (CalRecycle, 2006).

Compost amendments with a C:N greater than 30 have the potential to reduce crop yield due to nitrogen immobilization (Shiralipour et al. 1992). In composts with a C:N of 20 or less, usually 5 to 15% of total N becomes plant-available during the first year after application (Sikora and Szmidt 2001; Sullivan et al., 2003). Mupondi et al. (2006) and Warman and Termeer (1996) conducted bioassays and found that a mix of nutrient-rich material composted with a carboniferous material resulted in the strongest plant growth. The compost that performed the best for Mupondi et al. was a pine bark and goat manure blend with a C:N ratio of 16.

The use of immature compost with low C:N ratio can lead to phytotoxicity caused by the conversion of ammonium into ammonia in hot and moist conditions. The ammonia creates a toxic environment for plants and produces a foul odor (Roman et al. 2015; Azim et al. 2018). C:N ratio, is an important and commonly used compost quality parameter, though it must be noted, that it does not adequately predict nutrient mineralization or plant growth if viewed on its own, without complementary data (Griffin and Hutchinson 2007; Tognetti et al. 2011).

*Soluble Salts/Electrical Conductivity*

A low level of salinity is important in compost because it indicates the presence of nutrients in the form of cations and anions that are required for plant growth, but high salinity or high concentrations of organic acids can inhibit of germination and plant growth (Zmora-Nahum et al. 2007). Measurements of electrical conductivity indicate the presence of anions and cations of nutrients such as Ca, Mg, $SO_4$, $NO_3$, Na, Cl, B. Salts that contain sodium, chloride and boron may be toxic to some plants. Salt tolerance depends on plant species (Sullivan and Miller, 2001). Compost amendments that increase the soil soluble salt levels to 4 mmhos/cm or higher pose a risk to healthy plant growth (Gollardo & Nogales 1987), but many standard compost specifications set the maximum electrical conductivity levels as high as 10 mmhos/cm.

*Cation Exchange Capacity*

Humic compounds left behind after decomposition in the composting process have a high capacity to adsorb cations. The ability to easily exchange certain cations with others at the same binding sites is referred to as cation exchange capacity (CEC). CEC tends to increase as compost matures and organic materials are humified. Iglesias-Jiménez and Pérez-García (1991) stated that a CEC greater than 60 meq.100 g−1 of OM is required for compost to be considered mature (Azim et al. 2018). Higher CEC provides for greater buffering capabilities against changes in pH (Sullivan and Miller, 2001).

*Particle Size*

Particle size of the organic material affects both the composting process and the interactions of the finished product with the soil. During the composting process small particle sizes decrease the number of large pores and increase the distance that oxygen must diffuse through the pile. The shape and size of particles affects how they settle, ultra-fine or uniform particle size and shape could create tightly packed arrangements and reduce free air space. A single pass of a windrow turner can reduce the volume of a pile by 10% due to compaction. To achieve sufficient oxygen levels within the pile, particle size must be variable and not too small (Azim et al. 2018).

However smaller particles allow for larger surface area for microbial activity. Alsanius et al. (2016) found that if wood is chipped, microbial colonization is less efficient and overall windrow aeration is relatively poor, but if wood is shredded, microorganisms have better access to the material and aeration is significantly improved.

In the soil, N immobilization has often been related to large compost particle sizes, which are less transformed during the composting process than smaller particle sizes. This could be a positive quality if the goal is to avoid excess nitrogen loss from manure-based composts. Composts are often screened by different size meshes, depending on end-use and national regulations (Brinton 2000; Mazzarino et al. 2004). Understanding the effects of different size compost fractions on nutrient dynamics and compost performance in the soil could help lead to standardization of screening regulations (Leconte et al. 2011).

Mazzarino et al. (2004) studied the difference in quality between biosolids compost with a particle size greater than 0.5 cm, less than 0.5 cm and unscreened compost and found the use of unscreened biosolids composts or composts greater than 0.5 cm contributed to increased water and nutrient storage capacity, and decreased compaction and the risk of soil erosion. However, the presence of large particles with high C:N may also result in nitrogen immobilization. If compost producers are screening their product, perhaps different sized compost fractions can be utilized for different objectives with varying quality requirements.

Particle size is particularly tricky when it comes to laboratory testing of compost. There can be inconsistency of analytical results due to varying pre-treatment protocols in the form of sieving, drying and grinding. Many labs will screen out fractions greater than 10mm prior to analysis, but there is no standard rule, and some national programs recommend against screening for certain types of tests, particularly biological tests. There are even different handling and pre-treatment methods for a single compost sample, depending on which parameter is being measured. In some labs, respiration and soluble salt content are tested on sieved fractions while metals, OM and total-N are tested on the entire sample after drying and grinding. Since compost is not homogenous and drying can affect chemical traits differently, these preparation methods can potentially have a dramatic effect on analysis results (Brinton, 2000). This lack of standardization between labs and nations contributes to the confusion and hesitancy surrounding compost use.

*N-P-K*

Zhang et al. (2006) estimated that about 10% of nitrogen in MSW compost was available in the first year after incorporation, while Iglesias-Jimenez and Alvarez (1993) reported 16–21% of the total N in MSW compost was available 6 months after application when applied at rates equivalent to 10, 20, 30, 40, and 50 t $ha^{-1}$ to a ferrallitic soil. The MSW compost increased dry matter yield of perennial ryegrass, soil mineral N, and plant N uptake proportional to the applied rate (Iglesias-Jimenez and Alvarez 1993). Raviv (2005) stated that high quality composts used as a soil amendment for horticultural purposes should have an N content >1.8%.

Loper et al. (2013) stated that suggested rates of compost applications from 10 to 35% (by volume) to the top 15 cm of soil (Hawver and Bassuk, 2007; Urban, 2008) are likely to exceed the N and P requirements of ornamental landscape plants and result in nutrient leaching.

Higher losses of N, P, and K were reported under mixed ornamental landscapes than turf during the first year after planting (Erickson et al., 2001; Erickson et al., 2005). Erickson et al. (2005) suggested this was attributed to the lower root density and canopy cover of ornamentals when compared with turf the first year after planting.

Soil phosphorus concentration has been found to increase with increasing application rates of compost (Iglesias-Jimenez et al., 1993, Zhang et al., 2006). Iglesias-Jimenez et al. 1993 observed that MSW compost provided equivalent amounts of P to soil as mineral fertilizers. The danger is that excess P can be applied to soil when compost is applied to meet N requirements (Bar-Tal et al., 2004; Hargreaves et al. 2008).

Soumare et al. (2003) found 36–48% of total K in MSW compost was plant available. Experiments conducted in Germany showed that with regular compost applications of 6-10 tonnes/ha/yr, 30-50% of P is available and 40-55% of K is available. Increases of 1.0 mg P2O5/100g soil and 1.3 mg K2O/100g soil were found for each 100 kg of nutrient applied. There was a correlation observed between the rates of P and K applied and the increase of available P and K in the soil (Alsanius et al. 2016). Soil K concentrations have been found to increase even when very low rates of compost are used (Giusquiani et al., 1988). Compost application can provide a host of macro- and micro-nutrients to plants and soil biota. Increases in nutrients like Ca, S, Mg, Zn, and Cu have been observed (Warman et al., 2004; Zhang et al., 2006).

*Contamination*

Contamination is generally among the top concerns for compost users. All compost standards include compost sanitization criteria for human pathogens such as Salmonella, fecal coliforms and fecal streptococci, and some include plant pathogens as well. There are maximum permissible values for heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn) although these limits vary widely (Hogg et al. 2002). There are also maximum permissible values for inert foreign matter such as glass, plastics and stones, usually defined as maximum allowed content on a dry weight basis and in reference to their particle size (Brinton, 2000; Lasaridi et al. 2006). The biggest safety concern is regarding potentially toxic compounds (PCBs, PAHs, phthalates etc.) (Brinton, 2000; Hogg et al., 2002).

*Uncertainty*

The one quality that plagues all composts is uncertainty. Even in highly regulated, carefully monitored systems composts will vary from batch to batch. Many growers avoid using compost because of uncertainty about chemical and biological properties and appropriate application rates (Roe, 2003). Large scale compost producers are unlikely to be thinking about a specific end use when submitting samples to laboratories for testing and laboratories are generally unaware of the intended end use or they assume the end use is agricultural and base their recommendations on that assumption (Bonhotal et al. 2008).

**Specifications**

A specification is a legal document or contract describing a set of requirements that must be satisfied by a material or medium, in this case, compost. It is a technical standard used to communicate across industries between different kinds of specialists and practitioners. There are many compost specifications, each tailored to a particular use. The USCC has standardized specifications on their website available to practitioners and the public for the purposes of turf establishment with compost, planting bed establishment with compost, compost as a landscape backfill mix component, compost as a landscape mulch, compost as a soil blanket for erosion control and compost as a filter berm for sediment control (USCC 2005).

The parameters covered in a standard compost specification are pH, soluble salt concentration (mmhos/cm), moisture content (%), OM content (%), particle size (% passing a selected mesh size), stability (mg $CO_2$-C per g OM per day) and physical contamination (% of inerts). Specifications will occasionally also contain maturity based on a bioassay (% emergence and seedling vigor relative to positive control), chemical contamination (mg/kg), biological contamination (most probable number (MPN) of pathogens per gram). Specifications can also include a description of the compost amendment strategy, a list of materials, detailed instructions for use and a method of measurement (e.g. ton or cubic yard etc.) (USCC 2005; Alexander 2003).

Compost specifications can also specify feedstocks. In the Soil Profile Rebuilding specification written by Day et al. (2012), the accepted feedstocks specified are leaves, green waste and food waste. Biosolid-based composts are explicitly prohibited and a sample of the compost along with its lab analysis is required to be submitted for approval to the client before the application of the amendment.

Nutrient content is not often included in compost specifications, although it is generally included in compost laboratory testing. Nutrient content is an important consideration, not only for determining plant growth, but also to gauge to what extent nutrients might be lost after application.

Often, compost specifications provide the absolute minimum standards that must be met by a material for its use in a project. In the future, as our understanding of compost and its uses expand and as the science and technology of compost production advance, compost products will increasingly be able to meet the precise needs of end users and written specifications will have to evolve to reflect that (Fitzpatrick et al. 2005; Bonhotal et al. 2008).

**Benefits of Compost as a Soil Amendment**

Soils that have been greatly affected or manipulated by human activity are referred to as anthropogenic soils. Urban development typically results in loss of soil OM, loss of structure and permeability, and increased compaction. The effects of compaction include increased bulk density, decreased porosity, decreased aeration and infiltration capacity, increased runoff and erosion and restricted root growth, which makes horticultural activities very difficult (Somerville et al. 2018; Kozlowski 1999; Gregory *et al*., 2006; De Kimpe & Morel, 2000; Lehmann & Stahr, 2007).

*Compaction*

In degraded landscapes, Cogger (2005) says compost applications of 5 to 8 cm, amended 20 to 25 cm deep provide long-term improvement of soil health. Somerville et al. (2018) tested different strategies for remediating tree pits by tilling at two depths (0.25 and 0.5 m); half of the plots at each depth were amended with municipal green waste compost. The other half received no amendment. They found that all treatments improved the bulk density and hydraulic conductivity of the soil, but the treatments amended with compost maintained the improved bulk density longer term. Whether or not the added compost improved the hydraulic conductivity compared to tillage alone, depended on the soil type (Somerville et al. 2018). Sax et al. (2017) completed a twelve-year study that demonstrated that the combined practice of organic matter incorporation and physical fracturing improves bulk density over time. The study also showed that as OM increases, bulk density decreases. The decrease in bulk density was observed within a year of compost amendment and continued to decrease over the twelve years that were studied. Aggregate stability and aggregate size also increased in treated soils creating a structure more resistant to compression and increasing airspace between aggregates. Both studies utilized only one type of compost.

Cogger et al. (2005) stated that the greatest bulk density reductions after OM incorporation, occurred in coarse-textured soils and that soil organic C increased the most in cooler climates, where there is a slower rate of decomposition. Mohammadshirazi et al. (2017) found different results. They looked at the effects of tillage and compost amendment on bulk density and infiltration rate in different soil types. They found compost amendment improved bulk density more in soils with finer textures. They also observed improved infiltration rate with the addition of compost, compared to tillage alone, in only one of their five sites. They suggest tillage alone is a viable strategy for reducing bulk density and increasing infiltration for several years (Mohammadshirazi et al. 2017).

Rawls et al. (2003) found that increasing OM in coarse textured soils significantly increased available water holding capacity more than in fine textured soils. This effect was even more pronounced in soils with initially low OM levels, but if OM was already present at percentages greater than 5% AWHC increased regardless of soil textural class. The increased water holding capacity that results from compost incorporation can also buffer the threat of drought conditions, which can be particularly useful in agricultural soils. Greater AWHC further protects the plants from stress that might make them more vulnerable to attack from pathogens (Rawls et al. 2003).

*Microbial Activity*

Compost can serve many purposes in horticultural systems (Stofella and Kahn, 2001; Termorshuizen et al., 2004). Another benefit of incorporating compost is increasing soil OM and stimulating soil microbial communities (Lynch et al. 2005). OM consists of a many simple and complex C compounds that can provide energy to a variety of different organisms. Some of those organisms, like bacteria, can affect plant health by binding atmospheric N, mycorrhizal fungi can mobilize N, P and water within the soil. Organic amendments also affect soil respiration (Sikora and Rawls, 2000), aggregate stability, water infiltration and hydraulic conductivity and water holding capacity (Raviv 2005; Sax et al. 2017, Rivenshield & Bassuk, 2007; Sæbø and Ferrini 2006; Borken et al, 2004, Bernal et al., 1998, Lee et al., 2004).

Compost incorporation can also increase the disease suppressive nature of soil either indirectly by increasing the population of beneficial microorganisms to compete with disease-causing microorganisms in the soil or directly through antagonism and predation (Van Loon et al. 1998; Hoitink et al., 1991; Weltzien, 1989). Stan et al. (2009) stated that microorganisms found in compost contribute to the disease suppression through four different mechanisms: competition, antibiosis, parasitism/predation and induced systemic resistance within plants. In the 1960s, nurserymen started using bark composts to decrease losses by Phytopthora root rots and today this is common practice (Ownley & Benson 1991). Composts have also replaced methyl bromides in the nursery industry (Hoitink et al. 1991).

*Plant Nutrition*

Compost can also partially replace synthetic inputs by providing essential macro- and micro-nutrients. Incorporation of compost into soil increases the supply of nitrogen (N), phosphorus (P), and carbon (C) (Fortuna et al. 2003) as well as levels of micronutrients such as zinc (Zn), manganese (Mn), and copper (Cu) (Mikhailova et al. 2015). Unlike fertilizer however, many of the nutrients in compost are organically bound and insoluble, so they are not immediately available to vegetation. Compost must undergo a microbially-mediated mineralization process in which nutrients like ammonium ($NH_4^+$), nitrate ($NO_3^-$), and phosphate ($PO_4^{3-}$ ) are released in inorganic, soluble forms that can be utilized by plants (Brady and Weil 2008). This slow release of organically bound nutrients makes compost less susceptible to nutrient losses during heavy rain events than fertilizers. The soluble nutrient component in compost could still leach when compost is applied in areas prone to saturation, like riparian zones and in storm water management systems (Hurley et al., 2017).

The long-term N availability that compost provides in the soil is particularly important in urban areas, where landscapes get heavy use and often receive little regular maintenance or fertilization (Alexander 2001; Diaz et al. 1993). When installing urban landscapes with perennial grasses, compost often comprises 10-30% of the soil mix specification on a volume basis (McCoy 1992; Alexander 1996; Sullivan et al., 2003). Sæbø and Ferrini (2006) suggest that an annual top-application of compost, 2–3 cm year, may be better than one large application at landscape establishment, because it may serve a dual purpose, not only providing nutrients and OM, but also assisting with weed management, decreasing management costs in urban areas.

Leaf-based composts performed better than sphagnum peat moss when applied as an amendment in tree lawns (Wiseman et al. 2012). Sphagnum peat moss reduced microbial biomass C in the root zone by 47% compared to unamended sites and suppressed seasonal soil respiration relative to compost. Leaf-based compost increased microbial biomass C by 12% compared to unamended root zones (Wiseman et al. 2012). Sæbø and Ferrini (2006) found that incorporating compost improved root growth and increased stability in trees particularly in dry areas and in coarse-textured soils. However, they recommend composts be limited to amounts that supplies the plants with 100–120 kg of plant available nitrogen per hectare or less to avoid nitrogen loss. Layman et al. (2016) found that the soil profile rebuilding (SPR) (compost amendment via subsoiling to 60 cm + topsoil + rototilling) accelerated tree establishment and growth of urban trees in compacted soil.  After one growing season, trees planted in SPR plots had a 77% greater average increase in cross-sectional area compared to the control in all five tested species (Layman et al. 2016).

The benefits of compost are not limited to plants and soil. There are economic and social benefits as well. Compost use in landscaping is a cost-effective and a sustainable substitute for the use of synthetic fertilizers. Composting transforms an unwanted waste product into a stable, benign substance with less volume (Alexander 2001; Dickson et al. 1991; Dougherty 1998), whereas landfilling OM results in significant methane production and emission, which contributes to deterioration of the ozone layer (Termorshuizen et al., 2005).

**Drawbacks**

There are a few main drawbacks associated with composting and compost as a soil amendment that have been discussed in the literature. The first is the lack of consistency or predictability that compost offers growers. If the goal is to use compost as a fertilizer replacement, compost will not provide as much plant-available nutrition as rapidly as fertilizer will. It is also more difficult to measure the exact amounts of N, P and K being delivered to the soil because even compost from the same producer will vary between and even within batches. On the other hand, compost contains many nutrients that fertilizer does not, including micro-nutrients that plants only require in small amounts like iron, zinc, boron, manganese etc. If made improperly or misused, compost could inhibit growth, cause scorching, chlorosis or other kinds of damage or even kill vegetation. It is vital for practitioners to be aware of how different composts ought to be used and for compost producers to communicate clearly about their composting process and the attributes of their product as an amendment (Sæbø and Ferrini 2006).

The other main concern is leaching of nutrients either during the composting process or after application. Nitrogen loss during composting may be reduced by using feedstocks with a higher C:N ratio to immobilize the nitrogen or by lowering the pH of the compost mixture, which will reduce ammonia volatilization during the thermophilic stage of composting (Ekinci et al., 2000; (Raviv 2005). Nitrogen-rich composts may cause excessive nitrate leaching in the first year or two after application (Borken et al, 2004). Craul (1999) noted that compost amendment rates of 50% by volume or greater have been known to settle, causing waterlogging in urban soils. Borken et al. (2004) measured nitrogen leaching in a forested area and observed that the mineral soils acted as a significant sink for $NO_3^-$ and dissolved organic N. This was shown by a reduction of their outputs measured at 10 cm and 100 cm soil depth.

Amlinger et al. (2003) discouraged the use of very large amounts of compost as a soil amendment, especially in well-drained soils. Nutrient leaching from compost-amended soils could exacerbate existing eutrophication problems, which threaten the health of coastal and freshwater systems (Carpenter et al. 1998; Hurley et al. 2017). This danger is elevated when composts are applied in late autumn and winter when plants are not actively growing. Spring is the best time to apply compost, when plants can take up dissolved nutrients, so they don't end up polluting groundwater.

Confessor et al. (2009) observed variation in leaching by feedstock (farm, food, and yard wastes), but stated that the farm waste compost with the greatest level of maturity leached the greatest amount of $PO_4$, even though the P concentration of that compost was lower than for the composts derived from other feedstocks (Hurley et al., 2017). Sax et al. (2017) noted that after compost incorporation of 33% by volume in landscape beds, phosphorus levels in treated soils were above the optimal level, but were within normal ranges for unamended sites. Manganese was also slightly above the recommended levels in treated sites (Sax et al. 2017). Phosphorus is taken up by plants at different rates compared to nitrogen and as a result, P can accumulate in soils (Sharpley and Withers, 1994). This excess could potentially be avoided by using composts that do not include manure as a feedstock (Sax et al. 2017).

**Places for Growth in the Composting Industry**

The two main places for growth that will ease composting further into the mainstream are communication and legislation. The greatest barrier to the utilization of composts in agriculture and horticulture is the lack of communication between compost producers and end users. Particularly for livestock producers who also produce compost, manure management is their primary goal and there is a lack of information regarding the economic advantages of producing and marketing compost (Walker et al., 2006). It is unlikely that these producers are aware of their end users' material specifications. Additionally, growers requiring compost may not always have access to specifications or know where to look in order to choose a product that addresses their particular needs (Raviv, 2005). Different types of composts are suited for different uses, but in many cases connections between producers and users of compost are not made.

In the 2008 survey conducted by Bonhotal et al., performance in terms of plant production was a primary concern for compost users when choosing a product, but there was little agreement in the industry on which parameters of compost quality would predict satisfactory performance. Collaboration between compost producers and end users would allow producers to understand how their particular compost could best be marketed and utilized and would give growers the opportunity to have a say in the process and build important partnerships (Walker et al., 2006).

Another barrier aside from lack of knowledge and communication is a lack of infrastructure. Municipal composting facilities are designed and operated with the primary goal of diverting organic materials from landfills. These facilities do not have the mindset of manufacturing a marketable product. Altering this mindset is challenging. Many composting facility operators do not believe that there is a good market for high quality compost and if they do, manufacturing higher quality products requires money and substantial effort. However, it is crucial that the compost industry mindset changes from one of landfill diversion to one of product manufacturing if progress is to be made (Goldstein 2001; Walker et al., 2006).

Another hurdle lies in the way composts are researched. When specific composts are investigated, the conclusions drawn are limited to the compost in question. Because compost feedstocks are incredibly diverse, defining overarching guidelines for production and usage is impossible. Additionally, compost is rarely made with only one feedstock. Mixing of feedstocks is common practice in the industry and it is often necessary when trying to achieve optimal C, N and P ratios as well as adequate aeration (Zmora-Nahum et al. 2007).

Increasing legislation and enacting higher environmental standards resulted in the development of a new generation of composting facilities throughout Europe (Stan et al., 2009). Walker et al. (2006) explained that because of increased legislation throughout the U.S. such as the Illinois Livestock Management Facilities Act, an increasing number of livestock operators have expressed interest in incorporating composting of livestock waste into their manure management plans. In addition, where landscape wastes were banned from landfills the number of active compost facilities have greatly increased. In Illinois, where landscape waste was banned from landfills in 1990, the number of composting facilities is approaching the number of landfills (Walker et al. 2006).

Moving forward standardized testing protocols like the Test Methods for the Examination of Compost and Composting (TMECC), developed by the U.S. Composting Council (Thompson et al. 2002) will be crucial in advancing the use of compost in the landscaping industry. A recognized, consistent test protocol is critically important if one is to successfully adhere to written compost specifications and recommendations for use. We recommend compost producers and practitioners seek out labs that use TMECC. Compost is an extremely variable product. Standardization of testing is a good way to mitigate uncertainty and increase universal understanding of a complex product that is often made from a mix of feedstocks and by a variety of processes.

## Conclusion

Composting of the organic wastes created in our homes, yards, public spaces, institutions, factories and sanitation facilities is the most logical management option. With all these possible inputs the composting industry will continue to grow and evolve quickly. There must be a shift from mere waste diversion to diversion and high-value product manufacturing. Quality control and standardization of testing methods will be essential to make the most of this valuable resource and build trust among consumers.

When evaluating compost quality, it is crucial to look at multiple parameters. No single characteristic will offer an adequate picture of the quality of the compost or how that compost will interact with the soil or the landscape. Clear specifications aimed at specific soil remediation strategies will offer reliable usage information for growers and planners as well as assurance of success despite compost's variability. With continued research and collaboration between all stakeholders, clear standards, testing protocols, regulations and specifications can be created and customized to address each individual end-use and the groundwork can be laid for an evolving compost industry.

## References

Albrecht, R., Ziarelli, F., Alarcón-Gutiérrez, E., Le Petit, J., Terrom, G., & Perissol, C. (2008). 13C solid-state NMR assessment of decomposition pattern during co-composting of sewage sludge and green wastes. *European journal of soil science*, *59*(3), 445-452.

Albrecht R, Joffre R, Petit J, Terrom G, Périssol C (2009) Calibration of chemical and biological changes in cocomposting of biowastes using near-infrared spectroscopy. Environ Sci Technol Lett 43(3):804–811

Alexander, R. (1996). Field guide to compost use. *The Composting Council, Alexandria, VA*, *269*.

Alexander, R. (2001). Compost utilization in landscapes. *Compost utilization in horticultural cropping systems*, 151-175.

Alexander, R. (2003). Standard specifications for compost for erosion/sediment control. Apex, NC: Alexander Associates.

Alsanius, B. W., Blok, C., Cuijpers, W. J., França, S. C., Fuchs, J. G., Janmaat, L., & van der Wurff, A. W. (2016). *Handbook for composting and compost use in organic horticulture*. BioGreenhouse COST Action FA 1105.

Angers, D. A., & Recous, S. (1997). Decomposition of wheat straw and rye residues as affected by particle size. *Plant and Soil*, *189*(2), 197-203.

ATTRA – National Sustainable Agriculture Information Service. Sustainable Agriculture. Tipsheet: Compost. 2015. Tipsheet: Compost By Thea Rittenhouse, NCAT Agriculture Specialist. Published July 2015. https://www.ams.usda.gov/sites/default/files/media/Compost_FINAL.pdf

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., & Alami, I. T. (2018). Composting parameters and compost quality: a literature review. *Organic Agriculture*, *8*(2), 141–158. https://doi.org/10.1007/s13165-017-0180-z

Bar-Tal, A., Yermiyahu, U., Beraud, J., Keinan, M., Rosenberg, R., Zohar, D., ... & Fine, P. (2004). Nitrogen, phosphorus, and potassium uptake by wheat and their distribution in soil following successive, annual compost applications. *Journal of environmental quality*, *33*(5), 1855-1865.

Beniston, J. W., Lal, R., & Mercer, K. L. (2016). Assessing and Managing Soil Quality for Urban Agriculture in a Degraded Vacant Lot Soil. *Land Degradation & Development*, *27*(4), 996–1006. https://doi.org/10.1002/ldr.2342

Bernal M, Navarro A, Sánchez-Monedero M, Roig A, Cegarra J (1998) Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. Soil Biol Biochem 30(3):305–313

Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology*, *100*(22), 5444–5453. https://doi.org/10.1016/j.biortech.2008.11.027

Bollen GJ, Volker D & Wijnen AP (1989) Inactivation of soilborne plant pathogens during small-scale composting of crop residues. Neth. J. Plant Pathol. 95 (Suppl. 1), 19–30.

Bonhotal, J., Schwarz, M., Jack, A. L. H., Olmstead, D., & Harrison, E. Z. (2008). Compost Quality Assessment for Use in Horticulture: Impact of the Composting Process. Retrieved from http://ecommons.cornell.edu/handle/1813/46298

Borken, W., Xu, X.J., Beese, F., 2004. Ammonium, nitrate and dissolved organic nitrogen in seepage water as affected by compost amendments to European beech, Norway spruce and Scots pine forests. Plant and Soil 258, 121–134

Boulter-Bitzer J, Trevors J, Boland G (2006) A polyphasic approach for assessing maturity and stability in compost intended for suppression of plant pathogens. Appl Soil Ecol 34(1):65–81

Brady, N. C., and Weil, R. R. (2008). The nature and properties of soils, Pearson Education, Inc., Upper Saddle River, NJ.

Brinton, W. F., & Evans, E. (2000). Plant performance in relation to depletion, CO2-rate and volatile fatty acids in container media composts of varying maturity. In *Proceedings of the conference of Microbiology composting–Innsbruck* (Vol. 1, p. 12).

Brinton W.F. (2000) Compost Quality Standards & Guidelines. Woods End Research Laboratory. Final Report for New York State Association of Recyclers. http://compost.css.cornell.edu/Brinton.pdf

Brown, K. H., Bouwkamp, J. C., & Gouin, F. R. (1998). The influence of C: P ratio on the biological degradation of municipal solid waste. *Compost science & utilization*, *6*(1), 53-58.

Brown S, Miltner E, Cogger C. 2012. Carbon sequestration potential in urban soils. In Carbon sequestration in urban ecosystems, Lal R, Augustin B (eds). Springer: Dodrecht, Holland; 173–196

Bueno, P., Tapias, R., López, F., & Díaz, M. J. (2008). Optimizing composting parameters for nitrogen conservation in composting. *Bioresource Technology*, *99*(11), 5069-5077.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., and Smith, V. H. (1998). "Nonpoint pollution of surface waters phosphorus and nitrogen." Ecol. Appl., 8(3), 559–568.

Castaldi P, Alberti G, Merella R, Melis P (2005) Study of the organic matter evolution during municipal solid waste composting aimed at identifying suitable parameters for the evaluation of compost maturity. Waste Manag 25(2):209– 213

Chen, L., Dick, W. A., Streeter, J. G., & Hoitink, H. A. J. (1996). Ryegrass utilization of nutrients released from composted biosolids and cow manure. *Compost Science & Utilization*, *4*(1), 73-83.

Chen, Y., Day, S.D., Wick, A.F., Strahm, B.D., Wiseman, P.E., Daniels, W.L., 2013. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biol. Biochem. 66, 38–44.

CHRISTENSEN, B. T. (1986). Straw incorporation and soil organic matter in macro-aggregates and particle size separates. *Journal of Soil Science*, *37*(1), 125-135.

Cogger, C. G. (2005). Potential Compost Benefits for Restoration of Soils Disturbed by Urban Development. *Compost Science & Utilization; Abingdon*, *13*(4), 243–251.

Confesor, R. B., Jr., Hamlett, J. M., Shannon, R. D., and Graves, R. E. (2009). "Potential pollutants from farm, food and yard waste composts at differing ages: Leaching potential of nutrients under column experiments." Compos. Sci. Util., 17(1), 6–17.

Craul, P. J. (1999). *Urban Soils: Applications and Practices*. John Wiley & Sons.

Day, S. D., Layman, R. M., Chen, Y., Rolf, K., Harris, J. R., Daniels, W. L., Wiseman, P. E., McGuire, K. J., Strahm, B. D., Wick, A. F., Mauzy, B., 2012. Soil Profile Rebuilding Specification, Virginia Tech, urbanforestry.frec.vt.edu/SRES/ specification.html, doi: 10.13140/RG.2.1.3503.3049.

De Kimpe, C. R., & Morel, J.-L. (2000). Urban Soil Management: A Growing Concern. *Soil Science*, *165*(1), 31–40.

Delgado-Rodríguez, M., Ruiz-Montoya, M., Giraldez, I., Cabeza, I. O., López, R., & Díaz, M. J. (2010). Effect of control parameters on emitted volatile compounds in municipal solid waste and pine trimmings composting. *Journal of Environmental Science and Health Part A*, *45*(7), 855-862.

Dickson, N., Richard, T., & Kozlowski, R. (1991). *Composting to reduce the waste stream-A guide to small scale food and yard waste composting*. Northeast regional agricultural engineering service.

Dougherty, M. (1998). Composting for Municipalities: Planing and Design Considerations (NRAES-94). *Natural Resource, Agricultural and Engineering Service, Itacha, New York*.

Eiland, F., Klamer, M., Lind, A. M., Leth, M., & Bååth, E. (2001). Influence of initial C/N ratio on chemical and microbial composition during long term composting of straw. *Microbial Ecology*, *41*(3), 272-280.

Ekinci, K., Keener, H. M., & Elwell, D. L. (2000). Composting Short Paper Fiber with Broiler Litter and Additives. *Compost Science & Utilization*, *8*(2).

El Fels, L., Lemee, L., Ambles, A., & Hafidi, M. (2014). Identification and biotransformation of lignin compounds during co-composting of sewage sludge-palm tree waste using pyrolysis-GC/MS. *International Biodeterioration & Biodegradation*, *92*, 26-35.

Emino, E.R., Warman, P.R., 2004. Biological assay for compost quality. Compost Science & Utilization 12 (4), 342–348

Fierer, N. (2017). Embracing the unknown: disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology*, *15*(10), 579. https://doi.org/10.1038/nrmicro.2017.87

Fitzpatrick, G.E., E.C. Worden, and W.A. Vendrame. 2005. Historical development of composting technology during the 20th century. HortTechnology. 15: 48-51.

Forster, J. C., Zech, W., & Würdinger, E. (1993). Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. *Biology and Fertility of Soils*, *16*(2), 93-99.

Fortuna, A., Harwood, R., Kizilkaya, K., and Paul, E. A. (2003). “Optimizing nutrient availability and potential carbon sequestration in an agroecosystem.” Soil Biol. Biochem., 35(8), 1005–1013.

Gallardo-Lara, F., & Nogales, R. (1987). Effect of the application of town refuse compost on the soil-plant system: A review. *Biological wastes*, *19*(1), 35-62.

Goyal S, Dhull S, Kapoor K (2005) Chemical and biological changes during composting of different organic wastes and assessment of compost maturity. Bioresour Technol 96(14): 1584–1591

Gregory JH, Dukes MD, Jones PH, Miller GL. 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61: 117–124.

Griffin, T.S., Hutchinson, M., 2007. Compost maturity effects on nitrogen and carbon mineralization and plant growth. Compost Sci. Util. 15, 228–236.

Grosbellet, C., Vidal-Beaudet, L., Caubel, V., & Charpentier, S. (2011). Improvement of soil structure formation by degradation of coarse organic matter. *Geoderma*, *162*(1-2), 27-38.

Giusquiani, P. L., Marucchini, C., & Businelli, M. (1988). Chemical properties of soils amended with compost of urban waste. *Plant and Soil*, *109*(1), 73-78.

Hargreaves, J. C., Adl, M. S., & Warman, P. R. (2008). A review of the use of composted municipal solid waste in agriculture. *Agriculture, Ecosystems & Environment*, *123*(1), 1–14. https://doi.org/10.1016/j.agee.2007.07.004

Hogg, D., Favoino, E., Centemero, M., Caimi, V., Amlinger, F., Devliegher, W., Brinton, W., Antler, S., 2002. Comparison of compost standards within the EU, North America and Australia, The Waste and Resources Action Programme (WRAP), Oxon. ISBN 1-84405-003-3.

Hoitink, H.A.J., 1998. Control of nuisance and detrimental molds (fungi) in mulches and composts. Ohio State University Extension FactSheet HYG 3304-98.

Hoitink, H. A. J., Stone, A. G., & Han, D. Y. (1997). Suppression of plant diseases by composts. *HortScience*, *32*(2), 184-187.

Hubbe, M. A., Nazhad, M., & Sánchez, C. (2010). Composting as a Way to Convert Cellulosic Biomass and Organic Waste into High-Value Soil Amendments: A Review. *BioResources*, *5*(4), 2808–2854.

Hudson, B.D., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49, 189–194

Hurley Stephanie, Shrestha Paliza, & Cording Amanda. (2017). Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. *Journal of Sustainable Water in the Built Environment*, *3*(3), 04017006. https://doi.org/10.1061/JSWBAY.0000821

Iglesias-Jiménez, E., & Álvarez, C. E. (1993). Apparent availability of nitrogen in composted municipal refuse. *Biology and Fertility of Soils*, *16*(4), 313-318.

Iglesias-Jimenez E, Perez-Garcia V (1991) Composting of domestic refuse and sewage sludge. I. Evolution of temperature, pH, C/N ratio and cation exchange capacity. Resour Conserv Recy 6(1):45–60

Khater, E. (2015). Some physical and chemical properties of compost. *International Journal of Waste Resources*, *5*(01).

Kozlowski, T. T. (1999). Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*, *14*(6), 596-619.

Lasaridi, K., Protopapa, I., Kotsou, M., Pilidis, G., Manios, T., & Kyriacou, A. (2006). Quality assessment of composts in the Greek market: the need for standards and quality assurance. *Journal of Environmental Management*, *80*(1), 58-65.

Layman, R. M., Day, S. D., Mitchell, D. K., Chen, Y., Harris, J. R., & Daniels, W. L. (2016). Below ground matters: Urban soil rehabilitation increases tree canopy and speeds establishment. *Urban forestry & urban greening*, *16*, 25-35.

Leconte, M. C., Mazzarino, M. J., Satti, P., & Crego, M. P. (2011). Nitrogen and phosphorus release from poultry manure composts: The role of carbonaceous bulking agents and compost particle sizes. *Biology and Fertility of Soils, 47*(8), 897-906. doi:http://dx.doi.org.proxy.library.cornell.edu/10.1007/s00374-011-0591-z

Lee, J. J., Park, R. D., Kim, Y. W., Shim, J. H., Chae, D. H., Rim, Y. S., ... & Kim, K. Y. (2004). Effect of food waste compost on microbial population, soil enzyme activity and lettuce growth. *Bioresource Technology*, *93*(1), 21-28.

Lehmann, A., & Stahr, K. (2007). Nature and significance of anthropogenic urban soils. *Journal of Soils and Sediments*, *7*(4), 247–260. https://doi.org/10.1065/jss2007.06.235

Levis, J. W., Barlaz, M. A., Themelis, N. J., & Ulloa, P. (2010). Assessment of the state of food waste treatment in the United States and Canada. *Waste Management*, *30*(8), 1486–1494. https://doi.org/10.1016/j.wasman.2010.01.031

Lynch, D. H., Voroney, R. P., & Warman, P. R. (2005). Soil Physical Properties and Organic Matter Fractions Under Forages Receiving Composts, Manure or Fertilizer. *Compost Science & Utilization; Abingdon*, *13*(4), 252–261.

Mazzarino, M. J., Satti, P., Moyano, S., & Laos, F. (2004). Compost de biosolidos: Efecto del tamizado sobre la inmovilización de nitrogeno del suelo. *Ciencia del suelo*, *22*(1), 19-26.

McCoy, E. L. (1992). Quantitative physical assessment of organic materials used in sports turf rootzone mixes. *Agronomy Journal*, *84*(3), 375-381.

Mikhailova, E. A., Schlautman, M. A., Darnault, C. J. G., Sharp, J. L., Post, C. J., Hall, K. C., … Barfield, M. A. (2015). Effects of Compost on the Chemistry of an Urban Upper Piedmont South Carolina Soil. *Communications in Soil Science and Plant Analysis*, *46*(22), 2787–2797. https://doi.org/10.1080/00103624.2015.1089270

Mohammadshirazi, F., McLaughlin, R. A., Heitman, J. L., & Brown, V. K. (2017). A multi-year study of tillage and amendment effects on compacted soils. *Journal of environmental management*, *203*, 533-541.

Namkoong WE, Hwang Y, Cheong JG, Choi JY (1999) A comparative evaluation of maturity parameters for food waste composting. Compost Sci Util 7:55–62

Neklyudov, A. D., Fedotov, G. N., & Ivankin, A. N. (2008). Intensification of composting processes by aerobic microorganisms: A review. *Applied biochemistry and microbiology*, *44*(1), 6-18.

Ownley, B. H., & Benson, D. M. (1991). Relationship of matric water potential and air-filled porosity of container media to development of Phytophthora root rot of rhododendron. *Phytopathology*.

Pérez-Piqueres, A., Edel-Hermann, V., Alabouvette, C., & Steinberg, C. (2006). Response of soil microbial communities to compost amendments. *Soil Biology and Biochemistry*, *38*(3), 460–470. https://doi.org/10.1016/j.soilbio.2005.05.025

Raviv, M. 1998, Horticultural uses of composted material. In: R.A.K. Szmidt (Ed.). International Symposium on Composting and Use of Composted Materials for Horticulture. International Society Horticultural Science, Leuven 1, pp. 225–234.

Raviv, M. (2005). Production of High-quality Composts for Horticultural Purposes: A Mini-review. *HortTechnology*, *15*(1), 52–57.

Rawls, W., Pachepsky, Y., Ritchie, J., Sobecki, T., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76.

Rivenshield, A., Bassuk, N.L., 2007. Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboric. Urban For. 33, 140.

Roe, N.E. 2003. Why vegetable growers don't use compost. in M. Ozores-Hampton, N.E. Roe, and E. Hanlon (Eds.), Training in the Production and Utilization of Compost In Florida, Naples, FL, Florida Cooperative Extension Service: February 3

Román, P., Martínez, M. M., & Pantoja, A. (2015). Farmer's compost handbook. *Experiences in Latin America. Santiago: FAO*.

Rynk, R., 2003. The art in the science of compost maturity. Compost. Sci. Util. 11 (2), 94–95.

Sæbø, A., & Ferrini, F. (2006). The use of compost in urban green areas – A review for practical application. *Urban Forestry & Urban Greening*, *4*(3), 159–169. https://doi.org/10.1016/j.ufug.2006.01.003

Saha, J. K., Panwar, N., & Singh, M. V. (2010). An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices. *Waste Management*, *30*(2), 192–201. https://doi.org/10.1016/j.wasman.2009.09.041

Sax, M. S., Bassuk, N., van Es, H., & Rakow, D. (2017). Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. *Urban Forestry & Urban Greening*, *24*, 149–156. https://doi.org/10.1016/j.ufug.2017.03.023

Sharpley, N.S., Withers, J.A., 1994. The environmentally-sound management of agricultural phosphorus. Fertilizer Res. 39, 133–146

Shiralipour, A., McConnell, D. B., & Smith, W. H. (1992). Physical and chemical properties of soils as affected by municipal solid waste compost application. *Biomass and Bioenergy*, *3*(3-4), 261-266.

Sikora, L. J., & Rawls, W. J. (2000). In situ respiration determination as tool for classifying soils according to soil organic matter content. *Communications in soil science and plant analysis*, *31*(17-18), 2793-2801.

Sikora, L. J., & Szmidt, R. A. (2001). Nitrogen sources, mineralization rates, and nitrogen nutrition benefits to plants from composts. *Compost utilization in horticultural cropping systems. CRC Press, Boca Raton, FL*, 287-305.

Smith, D. C., & Hughes, J. C. (2001). A simple test to determine cellulolytic activity as indicator of compost maturity. *Communications in soil science and plant analysis*, *32*(11-12), 1735-1749.

Somerville, P. D., May, P. B., & Livesley, S. J. (2018). Effects of deep tillage and municipal green waste compost amendments on soil properties and tree growth in compacted urban soils. *Journal of environmental management*, *227*, 365-374.

Soumare, M., Tack, F. M. G., & Verloo, M. G. (2003). Characterisation of Malian and Belgian solid waste composts with respect to fertility and suitability for land application. *Waste Management*, *23*(6), 517-522.

Stan, V., Virsta, A., Dusa, E. M., & Glavan, A. M. (2009). Waste Recycling and Compost Benefits. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca; Cluj-Napoca*, *37*(2), 9.

Stoffella, P. J., & Kahn, B. A. (2001). *Compost Utilization In Horticultural Cropping Systems*. CRC Press.

Sullivan, D. M., & Miller, R. O. (2001). Compost quality attributes, measurements, and variability. *Compost utilization in horticultural cropping systems*, 95-120.

Sullivan, D. M., Bary, A. I., Nartea, T. J., Myrhe, E. A., & al, et. (2003). Nitrogen availability seven years after a high-rate food waste compost application. *Compost Science & Utilization; Abingdon*, *11*(3), 265–275.

Tang, J. C., Inoue, Y., Yasuta, T., Yoshida, S., & Katayama, A. (2003). Chemical and microbial properties of various compost products. *Soil Science and Plant Nutrition*, *49*(2), 273-280.

Termorshuizen, A. J., Moolenaar, S. W., Veeken, A. H. M., & Blok, W. J. (2004). The value of compost. *Reviews in Environmental Science and Bio/Technology*, *3*(4), 343–347. https://doi.org/10.1007/s11157-004-2333-2

Thompson, W., Leege, P., Millner, P., & Watson, M. E. (2002). Test methods for the examination of compost and composting (TMECC). *Reston, VA, USA: Composting Council*.

Tognetti, C., Mazzarino, M. J., & Laos, F. (2007). Improving the quality of municipal organic waste compost. *Bioresource Technology*, *98*(5), 1067–1076. https://doi.org/10.1016/j.biortech.2006.04.025

Tognetti, C., Mazzarino, M. J., & Laos, F. (2011). Comprehensive quality assessment of municipal organic waste composts produced by different preparation methods. Waste Management, 31(6), 1146–1152. https://doi.org/10.1016/j.wasman.2010.12.022

Tuomela, M., Vikman, M., Hatakka, A., & Itävaara, M. (2000). Biodegradation of lignin in a compost environment: a review. *Bioresource technology*, *72*(2), 169-183.

USCC. 2001. Field Guide to Compost Use. https://compostingcouncil.org/wp-content/plugins/wp-pdfupload/pdf/7984/Field_Guide_to_Compost_Use8x10.pdf

USCC. 2005. Landscape Architecture/Design Specifications for Compost Use. https://compostingcouncil.org/wp-content/plugins/wp-pdfupload/pdf/32/Landscape-Architecture-Specs.pdf

Van Loon LC, Bakker PAHM & Pieterse CMJ (1998) Systemic resistance induced by rhizosphere bacteria. Annu. Rev. Phytopathol. 36, 453–483

Vaughan, D., & Ord, B. G. (1985). Introduction soil organic Matter—a perspective on its nature, extraction, turnover and role in soil fertility. In *Soil organic matter and biological activity* (pp. 1-35). Springer, Dordrecht.

Walker, P., Williams, D., & Waliczek, T. M. (2006). An Analysis of the Horticulture Industry as a Potential Value-Added Market for Compost. *Compost Science & Utilization; Abingdon*, *14*(1), 23–31.

Weltzien, H.C. 1989. Some effects of composted organic materials on plant health. Agriculture Ecosystems & Environment. 27: 439-446.

Wiseman, P., Day, S., & Roger Harris, J. (2012). *Organic Amendment Effects on Soil Carbon and Microbial Biomass in the Root Zone of Three Landscape Tree Species, Poster Board #246* (Vol. 38).

Zaccheo, P., Ricca, G., & Crippa, L. (2002). Organic matter characterization of composts from different feedstocks. *Compost science & utilization*, *10*(1), 29-38.

Zhang, M., Heaney, D., Henriquez, B., Solberg, E., & Bittner, E. (2006). A four-year study on influence of biosolids/MSW cocompost application in less productive soils in Alberta: nutrient dynamics. *Compost science & utilization*, *14*(1), 68-80.

Zmora-Nahum, S., Hadar, Y., & Chen, Y. (2007). Physico-chemical properties of commercial composts varying in their source materials and country of origin. *Soil Biology and Biochemistry*, *39*(6), 1263–1276. https://doi.org/10.1016/j.soilbio.2006.12.017

CHAPTER 2: COMPOST QUALITY RECOMMENDATIONS FOR REMEDIATING URBAN SOILS


## Abstract

Compacted soil is a critical problem in many urban landscapes. Poor soil health restricts the ability of urban landscape plants to perform much needed ecosystem services. Amending soil with organic matter (OM) can increase porosity, infiltration, microbial biomass, cation exchange capacity, available water holding capacity, and structural stability. Incorporation of approximately 33% compost by volume into a landscape bed has been proven to improve soil health and structure over time while avoiding the financial and environmental costs of importing soil mixes from elsewhere. However, additions of high rates of compost can increase the risk of nutrient loss through leaching and runoff. The objective of our study was to consider the effects of different compost amendments on soil health, plant health and susceptibility to nutrient leaching in order to identify a range of acceptable compost characteristics that could be used for soil remediation in the urban landscape.

We conducted a bioassay with *Phaseolus vulgaris* (Bush Bean) to measure the effect of composts from different feedstocks (animal manure, green waste, food scraps) at different concentrations (33% and 50% by volume) on various plant health characteristics (dry shoot weight, leaf area and leaf greenness). We also collected leachate during the experiment to measure nutrient (nitrogen and phosphorus) loss from our different compost-amended soils.

We found carbon-rich green waste composts improved soil health the most, while nutrient-rich manure-based composts produced better plant growth. However, the manure-based composts that produced the largest plants, leached higher levels of N and P. Other amendments

provided sufficient nutrients for plant growth without excess nutrient loss. When choosing compost type, it is important to consider soil texture and understand the conditions and limitations of the intended site. We concluded, when incorporating as much as 33% compost by volume into a landscape bed, the optimal compost will generally have a C:N ratio of 10-20, P-content <1.0% and a soluble salt content between 1.0 and 3.5 mmhos/cm. These recommendations should ensure optimal plant and soil health and minimize nutrient leaching.

## Introduction

Healthy soils have the potential to provide critical ecosystems services through processes including nutrient cycling, water infiltration, pollutant containment and carbon sequestration in addition to providing habitat for plants, animals and microorganisms. An important indicator of soil health is good soil structure. Healthy soil forms aggregates, creating pore space that can be filled by air and water and ease the growth of plant root systems. This process is made possible by the organic matter in the soil and the organisms that consume and transform it, providing the binding agents that help form soil aggregates (Chen et al. 2014, Cogger 2005).

Urban soil is generally characterized by the disturbance inflicted upon it by human activity such as burying of construction materials, soil importing, contamination and compaction, which can lead to imperviousness and soil sealing. Urban soil also tends to lack OM and, as a result, exhibits little to no microbial activity (Craul, 1999; De Kimpe & Morel, 2000; Li et al, 2018). These characteristics make urban soil a poor habitat for plants and debilitate the growth of healthy urban ecosystems. To correct for this, the common practice in the landscaping industry is to remove and replace soils with specified soil mixes. These soil mixes are mined off-site and shipped to the desired location. This practice is costly and wasteful and does not address the underlying problem.

Compost amendment has been shown to improve physical, biological and chemical properties of many types of soil. It can decrease bulk density and increase porosity, OM content, microbial biomass, available water holding capacity, and structural stability (Mikhailova et al. 2015, Cogger 2005). However, compost is a highly variable product, which makes it difficult to assess quality and is, therefore, less appealing to landscape managers. Moving forward standardized testing protocols like the Test Methods for the Examination of Compost and Composting (TMECC), developed by the U.S. Composting Council (Thompson et al. 2002) will be crucial in advancing the use of compost in the landscaping industry.  In order to reap the full benefits of soil remediation with compost, one must fully understand the qualities of the compost being used, the qualities and limitations of the site and the desired outcomes.

A twelve-year study was completed at Cornell University in 2015, to measure the impacts of a soil remediation strategy on various soil quality indicators (Sax, et al. 2017). This strategy (The Scoop & Dump Method) consisted of physically fracturing compacted soils and incorporating large amounts of compost (33% by volume) to a depth of approximately 45 cm with the use of a backhoe or excavator.  After planting bark mulch was added to the soil surface. The study found that, over time, remediated soils exhibited improved bulk density, increased active C and increased mineralizable N, as well as improved aggregate stability and available water holding capacity. Chen et al. (2014) and Rivenshield & Bassuk (2007) discussed similar effects of compost on soil health, however, only one type of compost was tested in each of these studies. In this study, we sought to gauge the effects of different composts from different feedstocks on soil and plant health.

We conducted a bioassay with *Phaseolus vulgaris* (Bush Bean) to measure the effect of composts from different feedstocks (animal manure, green waste, food scraps) at different concentrations (33% and 50% by volume) on various plant health characteristics (dry shoot weight, leaf area and leaf greenness). We also collected leachate from each treatment during the experiment to measure nutrient (N and P) loss from our different compost-amended soils.

Nutrient leaching is a concern when high levels of compost are applied to landscapes before plant establishment or any time plants are unable to utilize large amount of N and P (Cogger 2005, Loper et al. 2013). Organic amendments are often applied at N-based rates, which can lead to applications of P in excess of plant needs and increase the likelihood of nutrient loss in leachate or runoff (Jaber et al., 2005). Our objective was to consider soil health, plant health and susceptibility to nutrient leaching in order to identify a range of acceptable compost characteristics that could be used for soil remediation in the urban landscape.

## Methods

### *Compost Selection*

In the autumn of 2017, we collected seventeen composts from around New York State. We collected composts from a variety of common compost feedstocks (e.g. manure, green waste, food scraps) and from a diversity of compost producers (e.g. farms, institutions, municipalities, private companies etc.). Approximately 75 liters of compost were collected from each location. We collected two different batches of compost from four of our producers. These batches were either prepared differently or a single company collected feedstocks from different locations. Most compost producers used a turned-windrow method of compost production (NRAES-54, 1992).

| Compost ID | Location | Major Feedstocks |
|---|---|---|
| **BOO** | **Greenwich, NY** | **Dairy Manure** |
| VA | Johnstown, NY | Dairy Manure |
| CV | Homer, NY | Dairy Manure |
| **CC** | **Trumansburg, NY** | **Food Scraps/Green Waste** |
| **CU** | **Ithaca, NY** | **Horse Manure/Green waste** |
| **DL** | **Stanfordville, NY** | **Horse Manure/Green Waste** |
| **WCE** | **Wolcott, NY** | **Poultry Manure** |
| OCJ | Jamesville, NY | Green Waste |
| OCS | Syracuse, NY | Green Waste |
| OH | Utica, NY | Green Waste |
| ORC | Orangeburg, NY | Green Waste (NY) |
| **OR** | **Orangeburg, NY** | **Green Waste (NJ)** |
| **FF** | **Staten Island, NY** | **Food Scraps** |
| FY | Staten Island, NY | Green Waste |
| BS | Bethlehem, NY | Green Waste (Screened) |
| **BL** | **Bethlehem, NY** | **Green Waste** |
| **CG** | **Ithaca, NY** | **Green Waste** |

**Table 1. Seventeen composts collected from around New York State.** Those in bold were selected for further experimentation.

A sample of each of the seventeen composts were brought to the Cornell University Nutrient Analysis Lab to be tested for C:N ratio by finding total carbon using the Combustion with $CO_2$ Detection and Total Kjeldahl Nitrogen. The compost samples were also tested for soluble salt content by measuring electrical conductivity using the slurry method as well as for OM% using the Loss on Ignition Method (LOI) all according to the Test Methods for the Examination of Composting and Compost (TMECC) protocol (TMECC, U. 2002). Based on those results we narrowed our study down to nine composts that represented a wide range of measured characteristics to use in our bioassay. Those nine composts were BOO, CC, CU, DL, WCE, OR, FF, BL and CG (Table 2).

| Primary Feedstock | ID | Organic Matter (%) | Total Ash Content (%) | Total N (%) | Organic N (%) | NH4 (mg/kg) | NO3 (mg/kg) | P2O5 (%) | K2O (%) | Ca (%) | Mg (%) | Total Carbon (%) | C: N | Soluble Salts (mmhos/cm) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YARD WASTE | CG | 35.27 | 78.33 | 0.82 | 0.82 | 10.94 | 5.15 | 0.22 | 0.57 | 5.20 | 0.75 | 22.32 | 27.26 | 1.01 | 8.25 |
| | OR | 72.91 | 78.76 | 2.83 | 2.83 | 2.06 | 19.85 | 0.53 | 1.53 | 4.33 | 0.70 | 71.63 | 25.40 | 1.32 | 7.52 |
| | BL | 65.60 | 81.58 | 2.93 | 2.91 | 2.86 | 242.88 | 0.73 | 1.79 | 4.88 | 0.94 | 55.62 | 17.22 | 2.64 | 7.54 |
| FOOD SCRAPS | FF | 25.50 | 95.39 | 1.62 | 1.61 | 2.98 | 100.90 | 0.63 | 0.84 | 4.16 | 1.10 | 20.82 | 13.13 | 0.85 | 8.06 |
| | CC | 24.23 | 95.70 | 1.64 | 1.60 | 5.98 | 410.80 | 0.82 | 1.41 | 2.22 | 0.57 | 17.40 | 11.53 | 1.94 | 7.66 |
| MANURE | DL | 84.80 | 88.97 | 3.99 | 3.92 | 8.20 | 626.18 | 1.03 | 2.52 | 8.46 | 2.49 | 64.70 | 15.91 | 3.21 | 8.15 |
| | CU | 83.23 | 138.11 | 3.38 | 3.34 | 13.17 | 439.74 | 2.20 | 4.42 | 7.44 | 1.98 | 54.01 | 15.95 | 2.21 | 7.29 |
| | BOO | 52.59 | 82.34 | 2.50 | 2.46 | 4.08 | 366.34 | 1.07 | 2.25 | 4.54 | 0.78 | 42.03 | 16.37 | 3.41 | 7.67 |
| | WCE | 50.68 | 39.44 | 6.49 | 6.18 | 3104.04 | 22.18 | 6.33 | 3.33 | 11.1 | 0.84 | 35.61 | 5.49 | 17.59 | 6.73 |

**Table 2. Compost characteristics.** This data table shows the mean of two samples of each compost tested at the Cornell Nutrient Analysis lab. Most of the tests shown above were taken according to the TMECC protocol. Nitrate and Ammonium content were found using a KCl extraction.

*Soil Amendment and Testing*

We collected an Arkport sandy loam soil (56% sand, 37% silt, 6% clay) from the Bluegrass Lane Turf and Landscape Research Center in Ithaca, NY and sifted that soil through a 2.0 cm sieve. This soil was mixed with each of the selected composts to make the media for our bioassay. The Arkport soil and the eighteen compost-soil mixes were all sent to the Cornell Soil Health Lab for testing prior to the bioassay and then twice more during the course of the experiment (Appendix A). The samples were stored in refrigeration at 4°C (40°F) prior to processing. Samples were analyzed for physical, biological and chemical indicators including available water holding capacity, aggregate stability, OM%, Autoclave Citrate Extractable (ACE) soil proteins, root pathogen pressure, soil respiration, pH, active C and extractible phosphorous using the Comprehensive Assessment of Soil Health: The Cornell Framework (Moebius-Clune et. al., 2016).

The OM% was determined by Loss on Ignition (LOI). Samples were dried at 105°C and weighed. The samples were then ashed for two hours at 500°C and weighed again and the percent of mass lost was calculated. Nutrients like phosphorous were extracted from soil mixes by shaking with Modified Morgan’s solution. After shaking, the extraction slurry was filtered and the filtrate was analyzed on an inductively coupled plasma emission spectrometer (ICP, Spectro Arcos).

We also measured soluble salts by making a 1:1 soil:water suspension by volume. The suspension was left to settle for one hour after which electrical conductivity of the supernatant was measured with a calibrated conductivity meter.

Available water holding capacity was tested by placing the soil on two ceramic plates and wetting them to saturation. The ceramic plates were then inserted into two high pressure chambers, one extracting the water to field capacity (10 kPa), the other to the permanent wilting point (1500 kPa). After each sample was weighed, oven-dried at 105◦ C to a constant weight, and then weighed again. The soil water content at each pressure was calculated, and the available water capacity was calculated as the difference between water content at 10 and 1500 kPa pressures (Reynolds et al. 2008).

To test for aggregate stability, soil was air-dried and shaken for 15 seconds on a Tyler Coarse Sieve Shaker to separate out aggregates of 0.25 - 2.0 mm size for analysis. A single layer of those aggregates was spread on a 0.25 mm sieve which was placed below a rainfall simulator. The simulator was run for 5 minutes and delivered 12.5 mm of water as drops to each sieve. The soil material that fell through during the simulated rainfall event, and any stones remaining on the sieve was collected, dried and weighed, and the fraction of stable soil aggregates was calculated (Moebius et al., 2007).

The Autoclaved Citrate Extractable (ACE) Protein Index indicated the amount of protein-like substances that are present in the soil OM. To extract the proteins, soil samples were placed into a glass tube with a sodium citrate buffer and shaken for 5 min at 180 rpm. A sample of the slurry was centrifuged at 10,000 x gravity to remove soil particles. A subsample of this extract was used in a standard colorimetric protein quantification assay (BCA) to determine total protein content of the extract. The Cornell Soil Health Lab used the Thermo Pierce BCA protein assay. Extractable protein content of the soil was calculated by multiplying the protein concentration of the extract by the volume of extractant used and dividing by number of grams of soil used (Wright and Upadhyaya 1996).

To test for active C, air dried soil was placed in a centrifuge tube with a 0.02 M potassium permanganate (KMnO4) solution, which is deep purple in color. The soil and KMnO4 were shaken for exactly 2 minutes to oxidize the active C in the sample which causes the solution to lose some of its color. The more active C found in the soil, the more color is lost. This color change was measured with a spectrophotometer and a simple formula was used to convert absorbance to active C in units of mg C per kg of soil (Weil et al., 2003).

Soil respiration was measured by placing a sample of air-dried soil in a glass jar. A trap assembly filled with an alkaline $CO_2$ - trapping solution (9 ml of 0.5 M KOH) was placed in the jar as well. Deionized water was then pipetted into the jar to rewet the soil and the jar sealed tightly and incubated undisturbed for 4 days. After incubation, the conductivity of the trap solution was measured. Trap electrical conductivity declined linearly with increasing $CO_2$ absorption. $CO_2$ respired was calculated by comparing the conductivities of the original trap solution, and a solution representing a trap saturated with $CO_2$ (Zibilske 1994; Moebius-Clune et al. 2016).

*The Bioassay*

Our nine selected composts were each combined with the sieved Arkport sandy loam soil to serve as the growing media for the bioassay. We made six repetitions of the following treatments, 100% soil, 100% compost for each of the nine composts, 50% of each compost with 50% soil by volume and 33% of each compost with 77% soil by volume.

For every repetition we used a #1 size nursery pot with a volume of 2.78 L (0.73 gallons). The 50% mixes were made by filling three pots to the first rim with soil (gently packed) and three pots with compost (gently packed). All six pots were combined in a large tub and mixed roughly with hands or trowel until evenly mixed. Then each of the six pots were refilled with the mixture distributed evenly by volume. For the 33% mixture a similar protocol was used. This time four pots were filled with soil and two pots were filled with compost and combined in the large tub. Both soils and composts were nearly completely dry when mixing took place with moisture contents below 5.0% for all media.

The bioassay was conducted in the greenhouse with *Phaseolus vulgaris* ‘Provider’ (bush bean) as our indicator species. Prior to planting, all treatments underwent a simulated heavy rain event. All pots were fully saturated, brought to container capacity (field capacity) and leachate was collected for later nutrient analysis. After that initial leaching, two *Phaseolus vulgaris* seeds were planted in each pot. Once the beans began to show true leaves if both plants had successfully germinated, one was disposed of. Pots were arranged in the greenhouse using a completely randomized design with six replicates and kept at 70°F and 16-hour days with overhead High Pressure Sodium High Intensity Discharge (HID) lamps. After germination, beans were watered with 150 ml of clear water every other day for the remainder of the experiment, excluding a second simulated heavy rain event conducted towards the end of the bioassay, for the purpose of collecting leachate. 150 ml of water was enough to keep the plants well-watered as they grew without allowing for more than slight leaching from the bottom of the pots.

Beans were harvested 39-42 days after they were planted. Soil was gently loosened around the roots to remove the plant to salvage as many roots as possible and collect a sample of the soil for testing. A SPAD 502 Plus Chlorophyll Meter (Konica Minolta, New Jersey, USA) was used to measure the "greenness" of the leaves. Leaf area was measured by taking a sample leaf from the second round of mature leaf growth from each plant and running it through a LI-COR 3100 leaf area meter (LICOR, Inc., Lincoln, NE). Shoots were separated from roots and placed in labeled paper bags and dried at 70°C for approximately two weeks after which dry shoot weight was measured.

*Leachate Testing*

Leachate was collected from each pot prior to planting and tested for nitrate, ammonium and soluble reactive phosphorus (SRP). Prior to planting the bean seeds, the media in each pot was saturated by putting each pot in a 5-gallon bucket, slowly filling the bucket with water until the water sat just above the level of the media in the pot and allowing it to soak for five minutes. Once pots were fully saturated, (bubbles no longer appeared at the surface and the pots sat on the bottom of the bucket) pots were placed upon plastic trays and left for 24 hours to reach "container capacity" (or field capacity). Container capacity of each pot was measured with a ThetaProbe Soil Moisture Sensor (Delta-T Devices Ltd, Cambridge, UK) and recorded. Any liquid in the tray was poured off and the trays were rinsed. We then poured 150 ml of clear water through the media and 40 ml of the leachate that came through the pot into the tray was collected. The 40 ml of leachate was then frozen for future analysis.

Leachate samples were thawed overnight prior to testing. Prior to phosphorus (P) testing, 20 ml of each sample was collected and filtered through 45µm filters. After filtering, samples were fed through an OI Analytical Phosphorus Analyzer Model 3000 (Xylem, Rye Brook, New York) using the Ascorbic Acid Method of phosphate analysis (Murphy and Riley, 1962). Nearly all the leachate samples that were collected exhibited some coloration most likely due to high levels of tannins in the OM. This posed a challenge when using a colorimetric method of nutrient analysis because the pigment in the samples could possibly interfere with the absorption of the color reagent being measured. For the phosphate analysis we diluted the darkest of our samples to overcome that interference. The darkest samples also showed levels of phosphorous that were well above the range of the instrument's rating curve so dilution was necessary to receive an accurate reading. We diluted all WCE (poultry manure) compost mixes at a ratio of 100:1 and both the 100% BOO (cow manure) and 100% CU (mixed horse manure and green waste) at a ratio of 10:1 with deionized water.

To measure Nitrate and Ammonium in the leachate, we used the colorimetric methods developed by Hood-Nowotny et al., 2010. This protocol was conducted using a Synergy™ HT Multi-Mode Microplate Reader (BioTek® Instruments Inc., Winooski, VT). Ammonium was quantified by a colorimetric method based on the Berthelot reaction (Kandeler and Gerber, 1988). Nitrate was estimated after persulfate oxidation by reduction of nitrate to nitrite by Vanadium (III) chloride and a colorimetric determination of nitrite by an acidic Griess reaction (Miranda et al. 2001). Dilutions were necessary once again and the dilutions differed between the first and second leach events. Dilutions also differed for Nitrate and Ammonium tests to ensure that the reading fell within the range that could be accurately read by the micro-plate reader.

Occasionally two different dilutions were made for a single treatment and an average was taken of the two readings.

### *Statistics*

Statistical analyses were conducted using JMP pro 14.0 (SAS Institute Inc., NC, USA). Tukey HSD was used to compare mean values of the six repetitions in the bioassay and leachate collections. Linear regression analyses were conducted to determine correlation between compost and amended soil characteristics and plant growth as well as nutrient leaching.

## Results

### *Soil Quality*

Compost amendment improved soil health regardless of feedstock type (Table 2) according to the Comprehensive Assessment of Soil Health completed at the Cornell Soil Health Lab (Moebius-Clune et al. 2016). Soil health tests were conducted on samples taken immediately after the incorporation of compost. Aggregate stability, OM percentage, soil respiration, ACE soil protein index and active C content increased for all amended soils compared to the control. Aggregate stability increased from 34.7% in the control soil to a minimum of 41.43% in the 50% DL treatment and a maximum of 68.50% in the 33% CU treatment. OM increased from 2.2% in the control to a minimum of 3.15% in the 33% OR treatment and 8.85% in the 50% BL treatment. ACE soil protein index score increased from 5.10 in the control soil to a minimum of 10.70 with the amendment of 33% CU compost and a maximum of 23.40 with the addition of 50% CC compost. Respiration increased from 0.40 mg $CO_2$ in the control to a minimum of 0.72 mg $CO_2$ in the 33% OR and a maximum of 1.98 mg $CO_2$ in the 50% CG treatment. Active C increased from 317.0 mg/kg in the control soil to a minimum of 487.58 mg/kg with the amendment of 33% DL compost and a maximum of 1160.90 mg/kg with the addition of 50% BL compost. Some of the amended soil mixes showed increased root pathogen pressure (50% CC, 50% and 33% CU). Manure-based compost mixtures generally exhibited higher values for root pathogen pressure, P and K content and soluble salt content and lower values for active C. For other soil characteristics like respiration, aggregate stability, available water holding capacity etc. feedstock type did not appear to have a noted effect.

Surprisingly, twelve of the eighteen amended soil mixes exhibited either no improvement or slightly decreased available water holding capacities. AWHC of amended soils ranged from 16.2% to 36.7% compared to soil alone, which was 22.0%. We surmise this may be due to the larger particle size of the nine composts which reduced bulk density and available water, but more research would be required to verify this. All compost amendments increased the soluble salt content of the soil, from 0.03 of soil alone to 0.126 mmhos/cm, at the lowest (33% FF) to 2.924 mmhos/cm, at the highest (33% WCE). All but six of the amended soil mixes displayed extractable P concentrations higher than 25 mg/kg MMP (Modified Morgan Phosphorus), making them potential sources of nutrient loss (Jokela et al. 1998; Moebius-Clune et al. 2016). The mixtures that did not were both concentrations (33% and 50%) of CG and OR compost as well as the 33% concentrations of the DL and FF composts. However, these mixes also showed the least impressive plant growth. The amended soil with the highest available P concentration was amended with 50% BOO containing as much as 180.137 mg/kg MMP, increased from the unamended soil concentration of 5.3 mg/kg of MMP.

| | | | Physical | | | Biological | | | | | Chemical | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Major Feedstock** | **ID** | **Compost Conc. (%)** | **Soil Texture** | **AWHC** | **Aggregate Stability (%)** | **OM (%)** | **ACE soil protein index** | **Root Pathogen Pressure** | **Respiration (mg)** | **Active C (mg/kg)** | **P (mg/kg)** | **K (mg/kg)** | **pH** | **Soluble Salts (mmho/cm)** |
| **Control Soil** | **S** | 0 | sandy loam | 0.22 | 34.70 | 2.20 | 5.10 | 4.00 | 0.40 | 317.00 | 5.30 | 20.10 | 5.40 | 0.03 |
| **Yard Waste** | **CG** | 50 | loam | 0.20 | 63.58 | 4.80 | 15.35 | 3.00 | 1.98 | 753.37 | 18.85 | 300.12 | 6.90 | 0.42 |
| | **CG** | 33 | sandy loam | 0.20 | 60.12 | 3.74 | 11.67 | 3.00 | 1.44 | 562.00 | 12.32 | 178.98 | 6.74 | 0.25 |
| | **OR** | 50 | sandy loam | 0.22 | 48.68 | 4.52 | 18.26 | 3.33 | 0.90 | 732.10 | 22.59 | 338.02 | 6.51 | 0.25 |
| | **OR** | 33 | sandy loam | 0.19 | 50.40 | 3.15 | 12.78 | 3.33 | 0.72 | 553.14 | 11.60 | 182.86 | 6.19 | 0.20 |
| | **BL** | 50 | loam | 0.37 | 62.91 | 8.85 | 20.26 | 3.75 | 1.15 | 1160.90 | 130.82 | 955.36 | 7.09 | 0.88 |
| | **BL** | 33 | sandy loam | 0.24 | 57.14 | 4.97 | 15.81 | 3.00 | 0.83 | 918.15 | 49.00 | 429.28 | 6.75 | 0.51 |
| **Food Scraps** | **FF** | 50 | sandy loam | 0.21 | 49.89 | 5.38 | 11.83 | 4.00 | 1.29 | 827.78 | 46.09 | 315.95 | 7.26 | 0.15 |
| | **FF** | 33 | sandy loam | 0.20 | 50.13 | 3.57 | 13.15 | 3.75 | 0.99 | 629.33 | 24.89 | 199.10 | 6.92 | 0.13 |
| | **CC** | 50 | loam | 0.24 | 51.49 | 6.64 | 23.40 | 6.67 | 1.31 | 951.82 | 126.33 | 1192.96 | 6.67 | 1.12 |
| | **CC** | 33 | loam | 0.20 | 57.88 | 4.55 | 18.20 | 3.00 | 1.13 | 758.68 | 69.08 | 700.34 | 6.67 | 0.76 |
| **Manure** | **DL** | 50 | loam | 0.27 | 41.43 | 5.74 | 16.01 | 3.25 | 1.32 | 707.30 | 59.62 | 621.65 | 7.13 | 0.54 |
| | **DL** | 33 | sandy loam | 0.20 | 48.99 | 3.70 | 11.61 | 3.50 | 0.95 | 487.58 | 21.11 | 314.55 | 6.29 | 0.35 |
| | **CU** | 50 | loam | 0.19 | 64.05 | 5.24 | 14.39 | 5.00 | 1.08 | 570.86 | 149.41 | 1017.41 | 6.85 | 0.82 |
| | **CU** | 33 | sandy loam | 0.18 | 68.50 | 4.07 | 10.70 | 5.75 | 0.94 | 487.58 | 68.36 | 572.86 | 6.48 | 0.57 |
| | **BOO** | 50 | sandy loam | 0.24 | 58.54 | 5.40 | 15.92 | 3.00 | 0.98 | 664.77 | 180.14 | 1330.43 | 6.91 | 0.90 |
| | **BOO** | 33 | sandy loam | 0.19 | 60.38 | 4.31 | 11.79 | 4.00 | 0.85 | 579.72 | 130.63 | 965.05 | 6.25 | 0.81 |
| | **WCE** | 50 | loam | 0.17 | 64.12 | 6.91 | 53.25 | 5.80 | 4.90 | 918.15 | 1021.00 | 2515.26 | 6.69 | 2.04 |
| | **WCE** | 33 | sandy loam | 0.16 | 63.34 | 5.81 | 30.27 | 4.33 | 4.91 | 538.97 | 637.04 | 1780.03 | 7.05 | 2.92 |

**Table 3. Unamended and amended soil characteristics.** The soil used in all mixes is an Arkport sandy loam. Samples were taken immediately after mixing. Tests followed the *Comprehensive assessment of soil health: the Cornell framework manual* protocol by Moebius-Clune.

BL leaf compost was the finest in texture with 63.2% of the compost particles smaller than 2.0mm, followed by CC with 60.1% smaller than 2.0mm. OR and DL composts were the coarsest in texture with 33.5% and 32.3% of compost particles being larger than 1.0 cm, respectively (Figure 1).

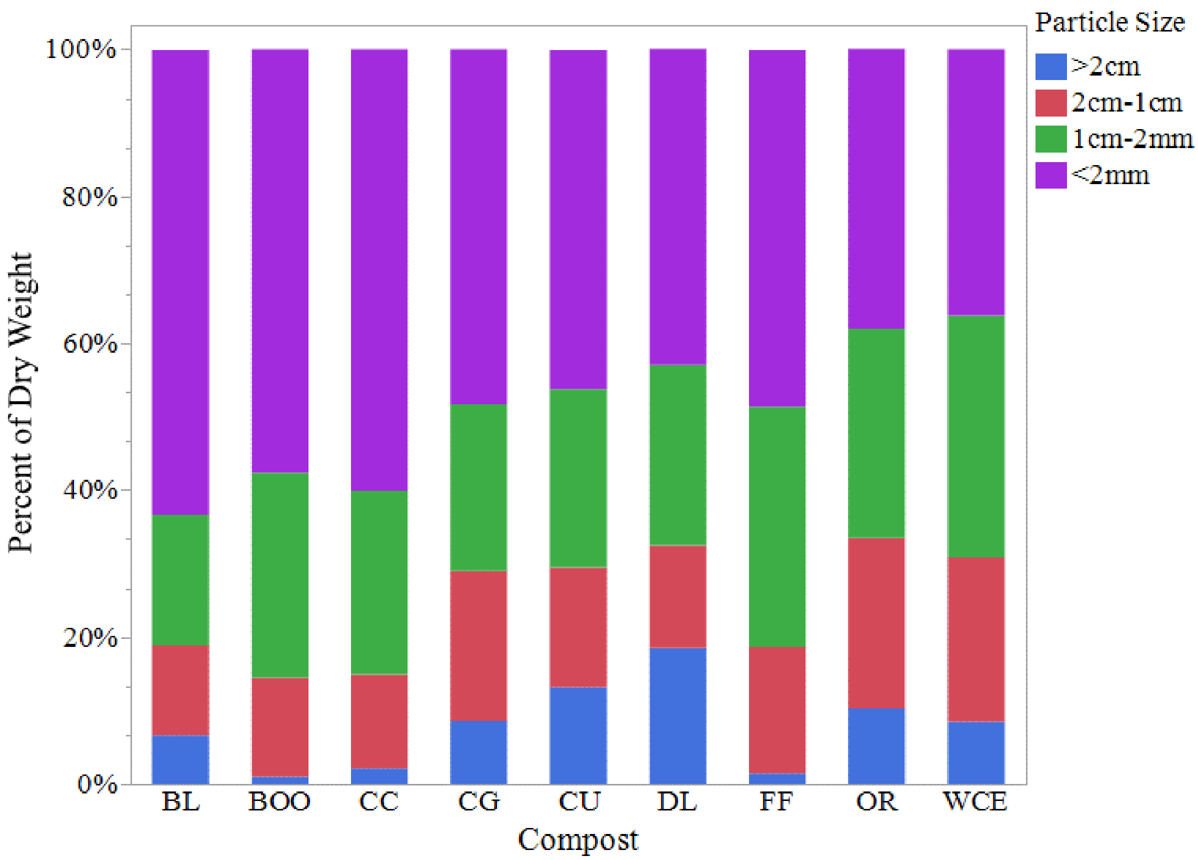


**Figure 1. Composition of the compost particle size** (>2cm, 2cm-1cm, 1cm-2mm, <2mm) by dry weight.

*Relationship of Compost to Plant Quality*

The compost characteristics that had the greatest effect on plant growth were C:N ratio (Figure 2), soluble salt content (Figure 3), Phosphorus (P) content (Figure 4) and Potassium (K) content. Soluble salt content of the amended and unamended soil had relatively strong positive correlations with both bean shoot weight and leaf area with $r^2$ values of 0.57 and 0.51, respectively. Extractable P of the amended soil had a strong, positive correlation with plant growth. Leaf area and shoot weight had $r^2$ values of 0.636 and 0.698, respectively, with increasing available P (Figure 4). The positive correlation between K content of amended soils and plant growth was also strong with $r^2$ values of 0.597 for leaf area and 0.652 for shoot weight.

OM% of the composts and amended soils, alternatively, showed no correlation with plant growth (Figure 5).

When composts with a C:N above 25:1 were incorporated into the soil, plant growth and chlorophyll concentration were reduced compared to the control. Shoot weight was reduced by as much as 80.9%, leaf area was reduced by as much as 77.3% and Leaf SPAD (greenness) was reduced by as much as 67.9% (33% OR compost) (Figures 6-8). Beans grown using composts with a C:N close to 15:1 displayed the greatest shoot weight and leaf area (Figures 6 and 7). C:N ratio and nitrate concentration of the compost had the greatest effect on chlorophyll concentration (Figure 8).

Manure-based composts outperformed the woody green waste-based composts, in terms of plant growth (Figures 6-8). The only plant health parameter that did not differ based on compost type was root length. We suspect the size of the pot may have constrained root growth. BOO and CU had the greatest shoot weights (Figure 6), leaf areas (Figure 7) and shoot lengths. The treatments displaying the highest leaf SPAD (chlorophyll concentration) were the 33% CC, with a measurement of 35.6 and the 0% compost (control soil), at 35.5 (Figure 8). We suspect that the bean plants grown in soil alone had highly concentrated chlorophyll because those plants were stunted in size with abnormally small leaves. CG and OR performed poorest in all categories. We do not have plant growth measurements for the poultry manure compost (WCE) because the bean seeds were unable to germinate at any compost concentration. WCE compost had a soluble salt content of 17.585 mmhos/cm, a C:N ratio of 5.87, ammonium concentration of 3104.04 mg/kg and a P concentration of 63,260 mg/kg. We excluded the WCE compost from our analysis as an extreme outlier. Poultry manure compost is generally marketed for use as an agricultural fertilizer rather than as a soil amendment in landscape beds.

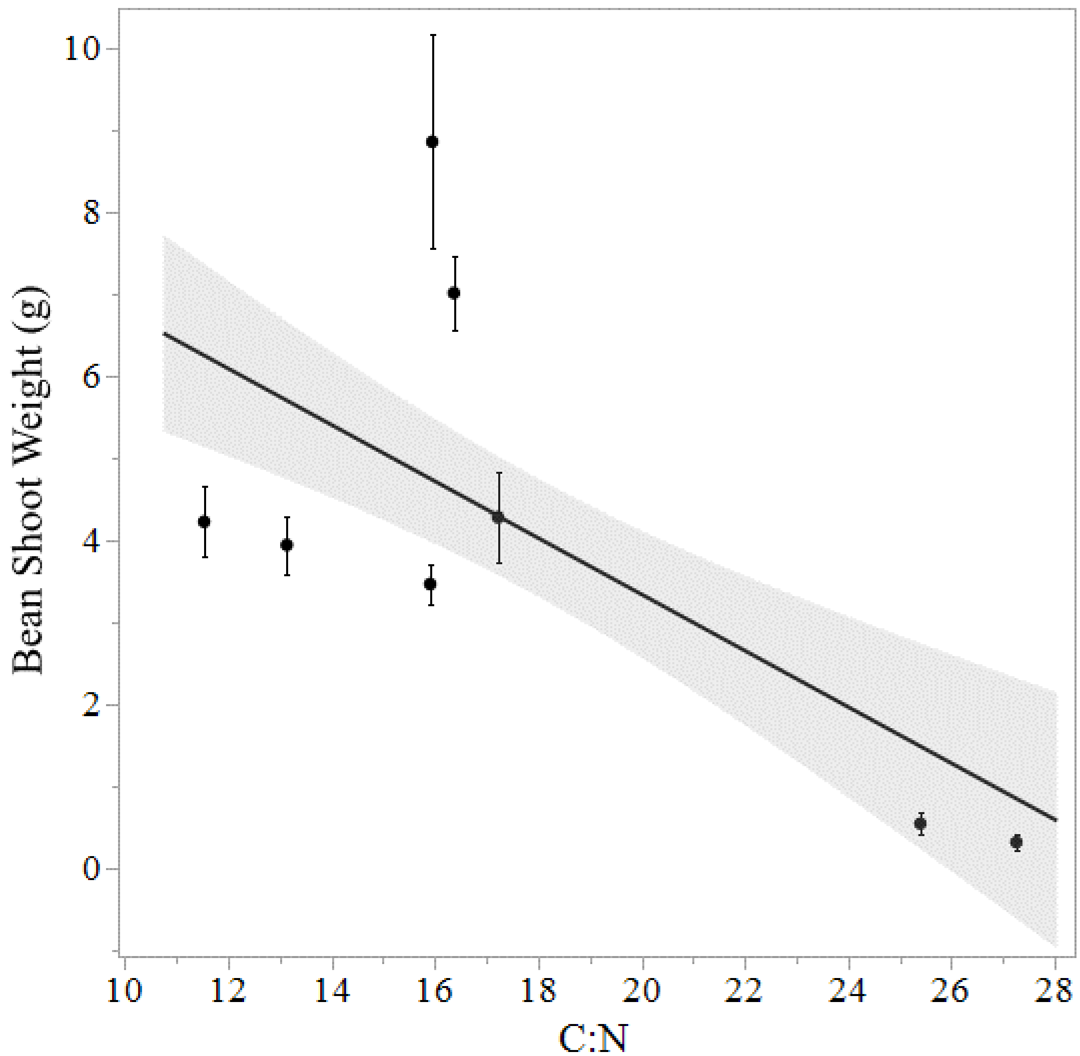


**Figure 2. Relationship between dry shoot weight of the bean plants and Carbon to Nitrogen ratio** of eight of the nine compost types (excluding WCE poultry manure compost). The black line represents the line of best fit; r2=0.359. The shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote standard error (n=6).

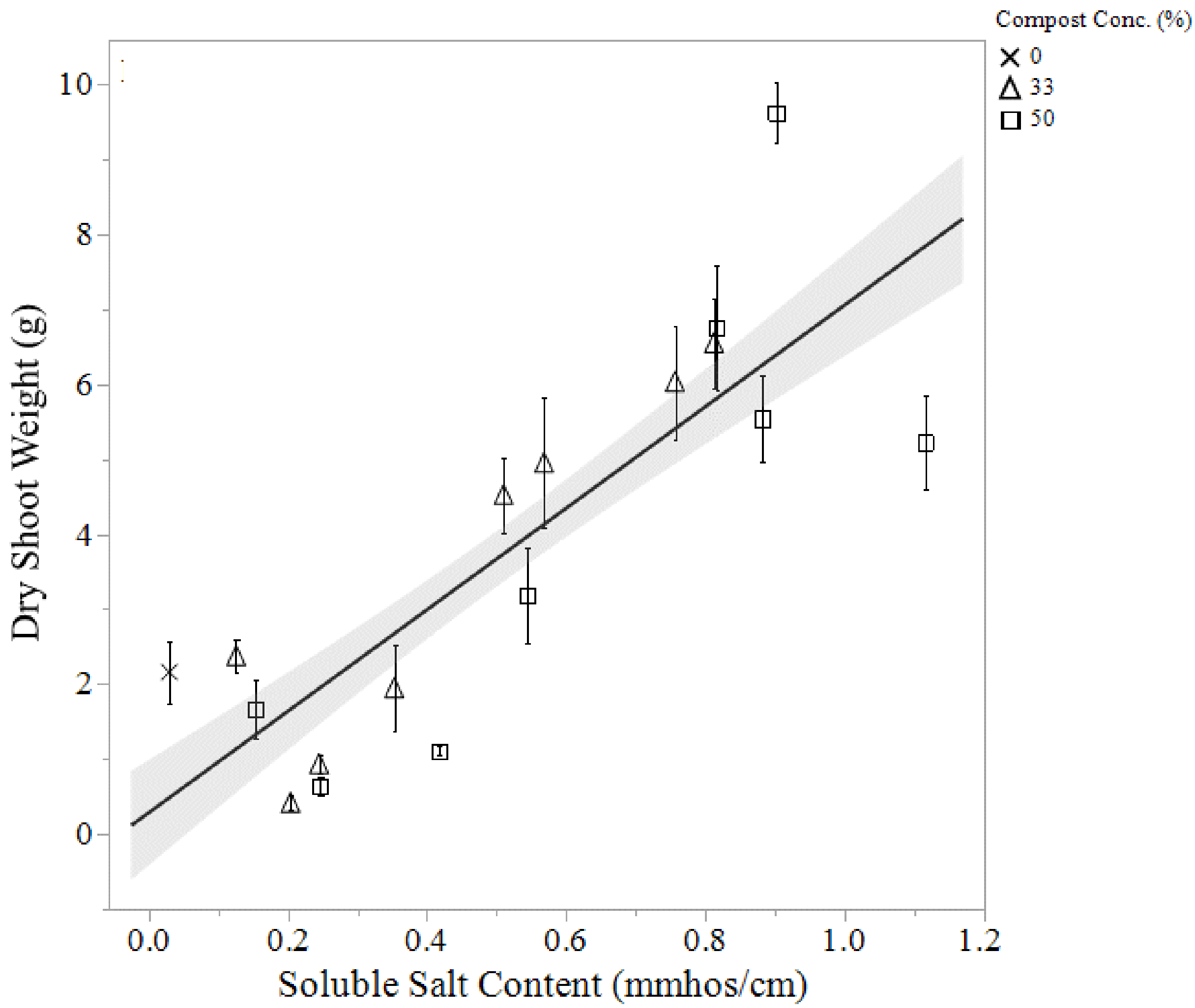


**Figure 3. Relationship between dry shoot weight of the bean plants and soluble salts concentration of the amended and unamended soil** for all compost types (excluding WCE poultry manure compost). The 100% compost treatments were not included in this graph for ease of interpretation. The black line represents the line of best fit; $r^2$=0.570. The shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote standard error (n=6).

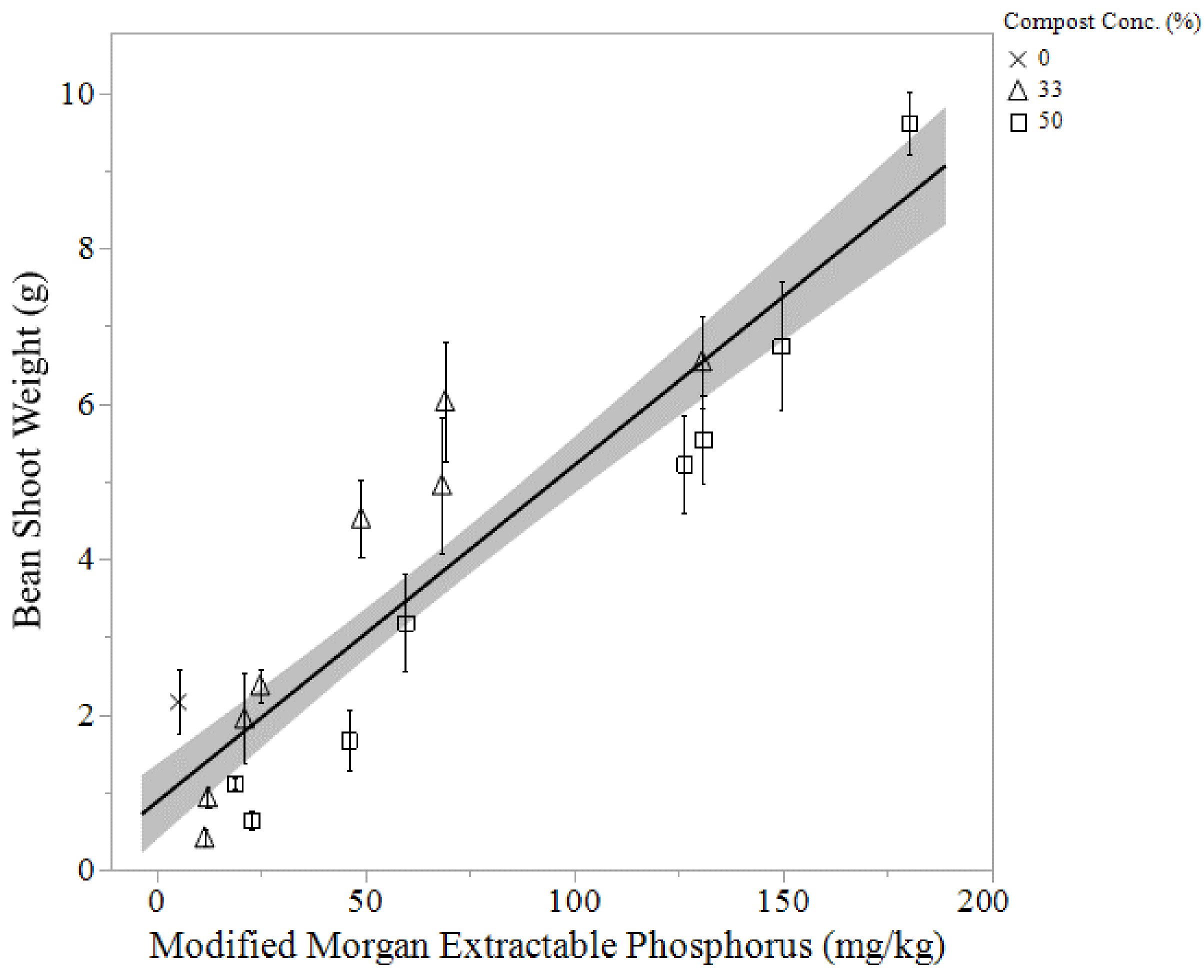


**Figure 4. Relationship between extractable (available) phosphorus content of the 33% and 50% amended soil and control treatments and bean dry shoot weight.** Extractable phosphorus of the 100% compost treatments was not included in this graph for ease of interpretation. The black line represents the line of best fit; $r^2$=0.698. The shaded area denotes a 95% confidence interval. Each point represents the mean of a single compost treatment, error bars denote standard error (n=6).

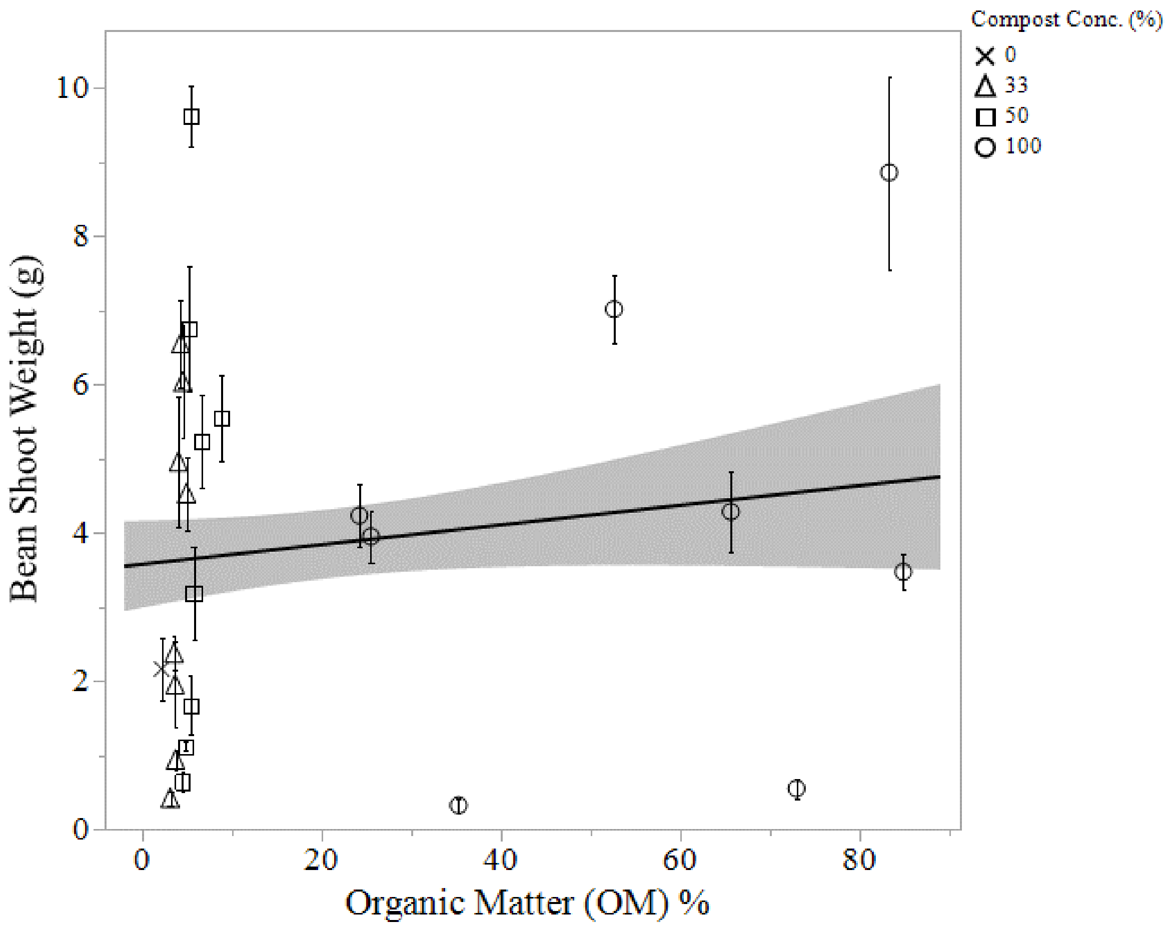


**Figure 5. Relationship between dry shoot weight of the bean plants and OM% of the growing media** for all compost types (excluding WCE poultry manure compost) at all three concentrations. The black line represents the line of best fit; $r^2$=0.016. The shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote standard error (n=6).

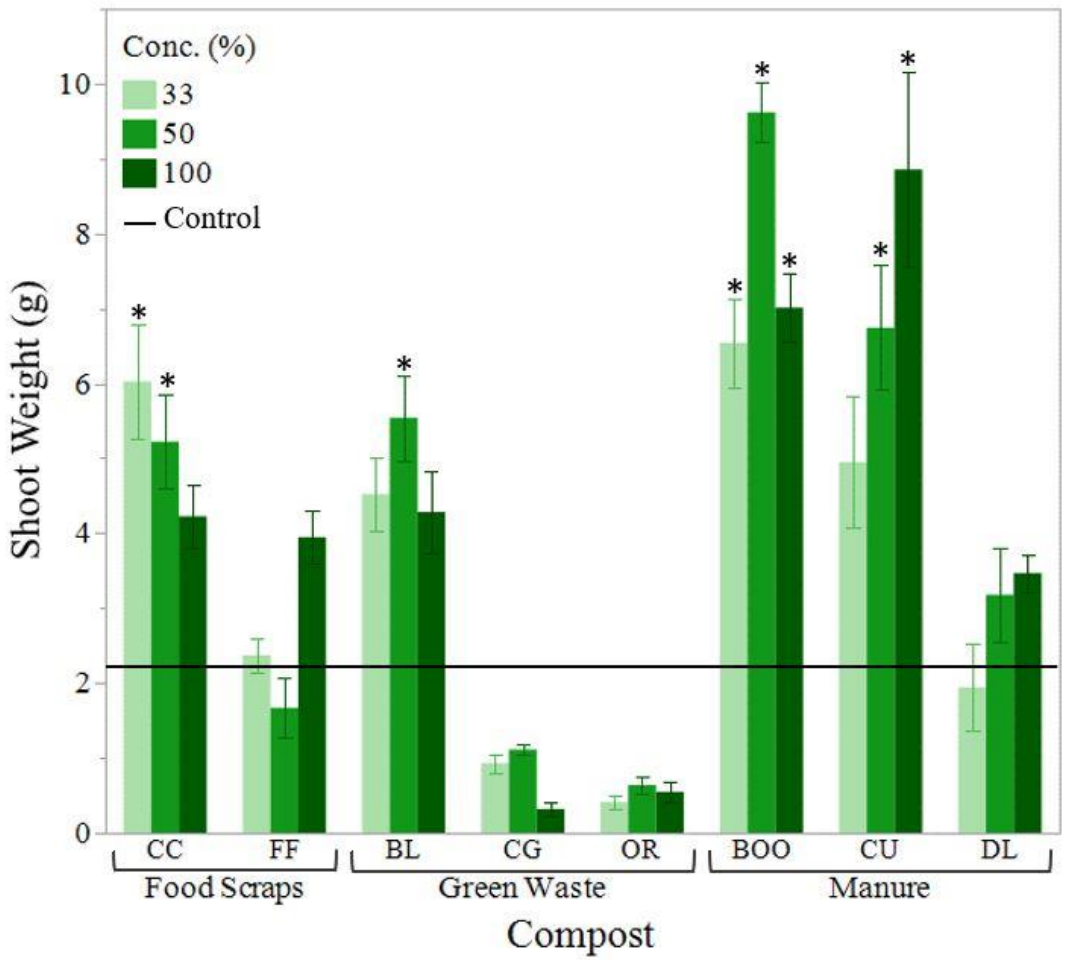


**Figure 6. Mean bean plant dry shoot weight in grams by compost type.** Compost concentration of the growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*) indicate significant difference from the control (α=0.05).

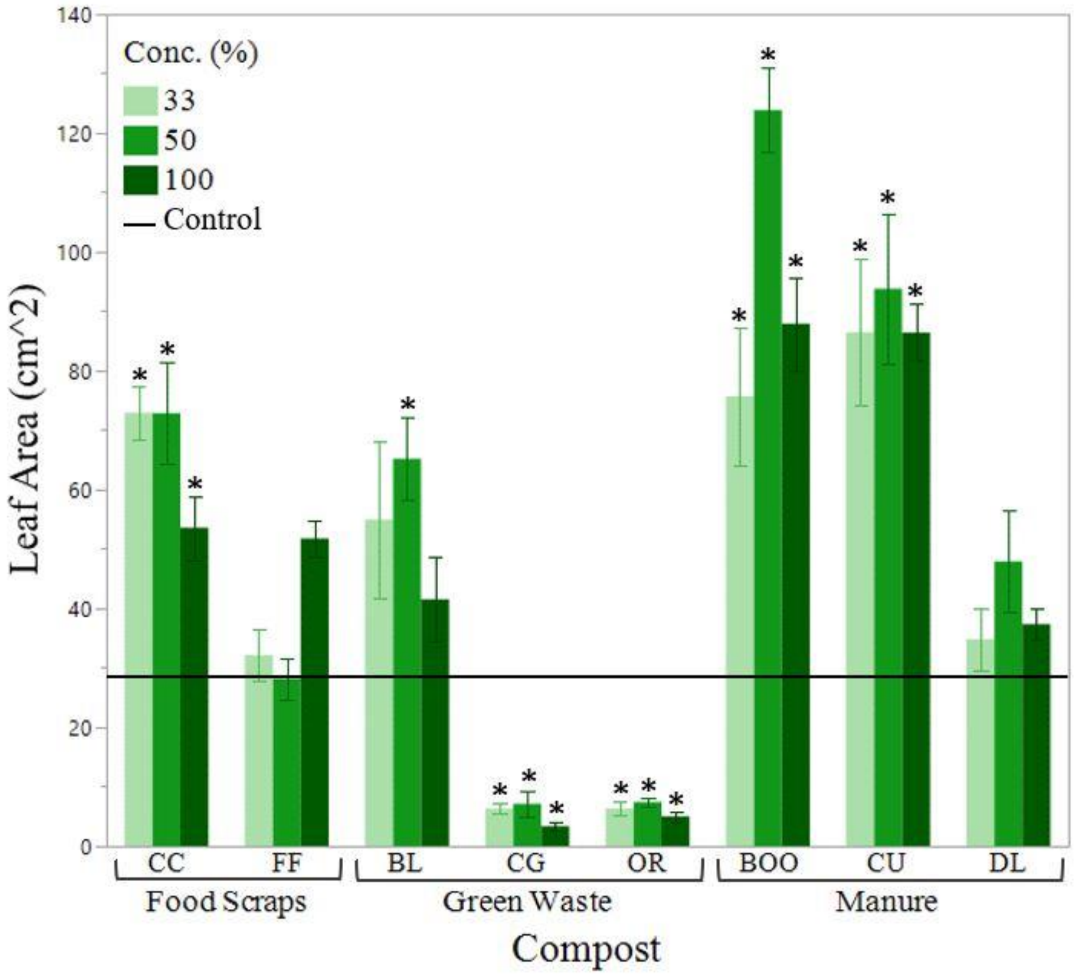


**Figure 7. Mean bean plant leaf area in cm$^2$ by compost type.** Leaf area was taken for the second round of growth on bean plants. Compost concentration of the growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

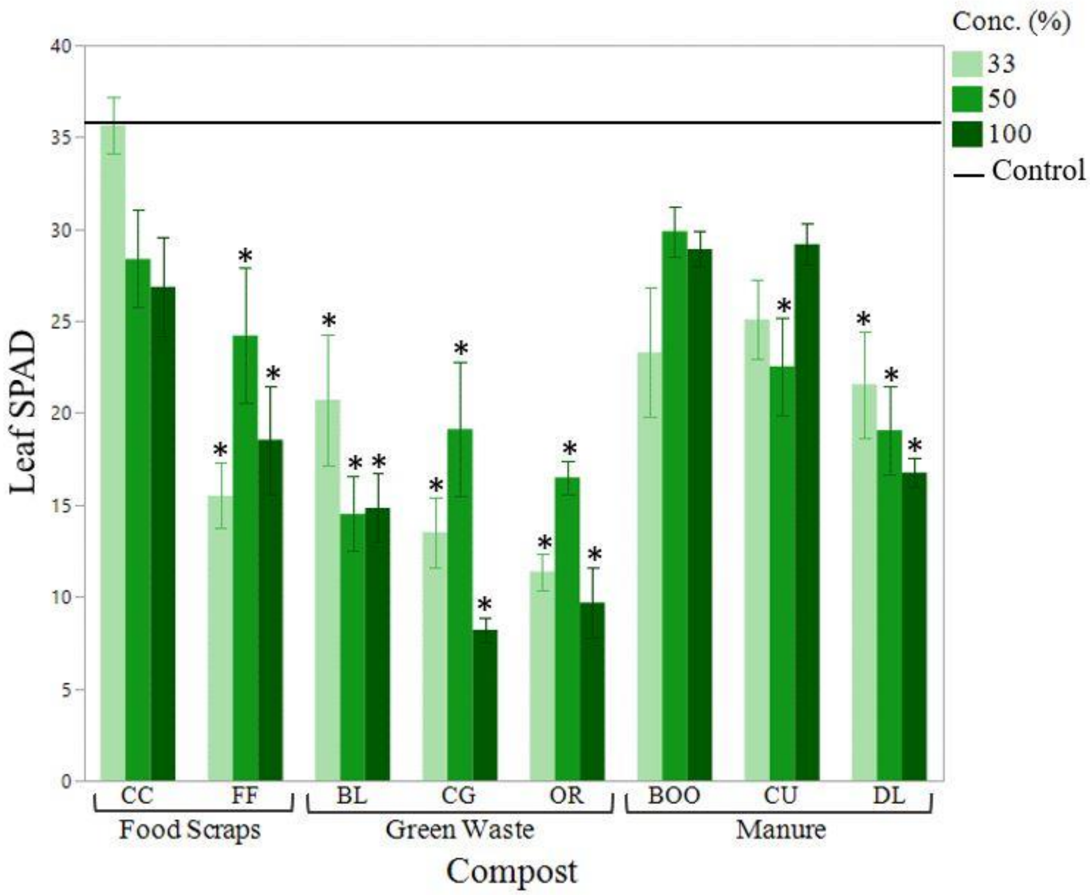


**Figure 8. Mean bean leaf SPAD (greenness) by compost type.** SPAD was taken using the second round of growth on bean plants. The mean of four separate measurements with the SPAD-meter was calculated for each plant. Compost concentration of the growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

*Nutrient Leaching*

We found a relatively strong positive correlation between extractable P content of composts and amended soils and SRP content of leachate (Figure 9). The same was not true for leached N, which displayed a weak correlation between nitrate found in the compost and nitrate content of the leachate (Figure 10). Three of the four manure-based composts used (BOO, CU, WCE) leached significantly higher concentrations of SRP than the rest of the composts (Figure 11). The composts that leached the greatest concentration of nitrate were CC and BOO followed by CU (Figure 12). And the WCE compost was the only one to show significant amounts of ammonium leaching. We excluded WCE from our analyses as an outlier. The 100% CU compost treatment leached the highest concentration of SRP at 32.395 mg/kg SRP, while the 33% CU compost treatment leached only 3.985 mg/kg SRP. The 100% CC (food scraps) compost leached 340.417 mg/kg $NO_3$, while the 33% CC compost treatment leached a far lower concentration, at 54.533 mg/kg $NO_3$. Planting directly into 100% compost is not recommended. The leachate measured was collected prior to planting. It is possible that the high concentrations of nutrients found in the leachate would decrease significantly after even a short period of time, especially with the presence of actively growing plants to utilize some of the nutrients.

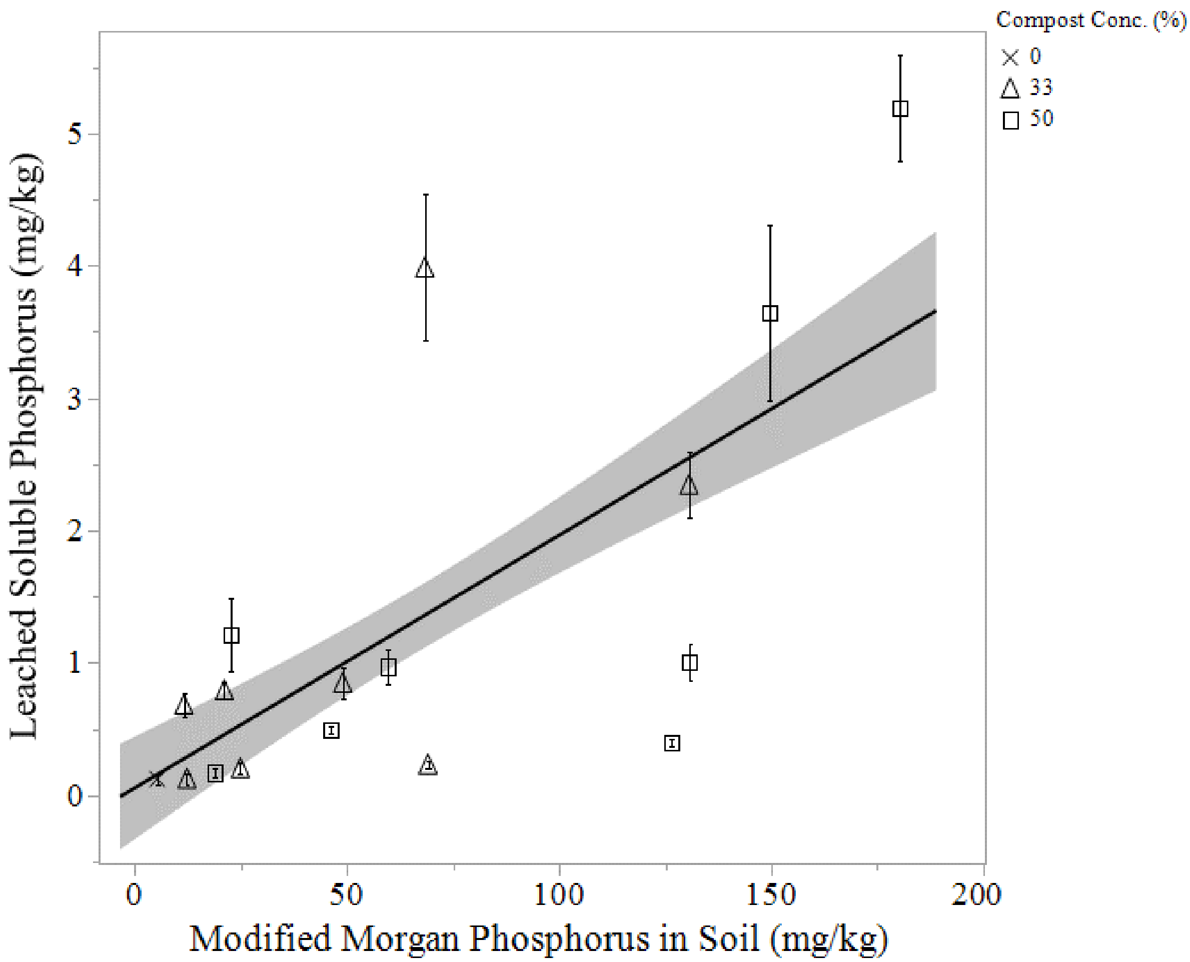


**Figure 8. Relationship between extractable (available) phosphorus content of the amended and unamended soil with concentration of soluble reactive phosphorus found in leachate.** This graph includes only the 33% and 50% compost amendments along with the control for ease of interpretation. The black line represents the line of best fit; $r^2$=0.417. The shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote the standard error (n=6).

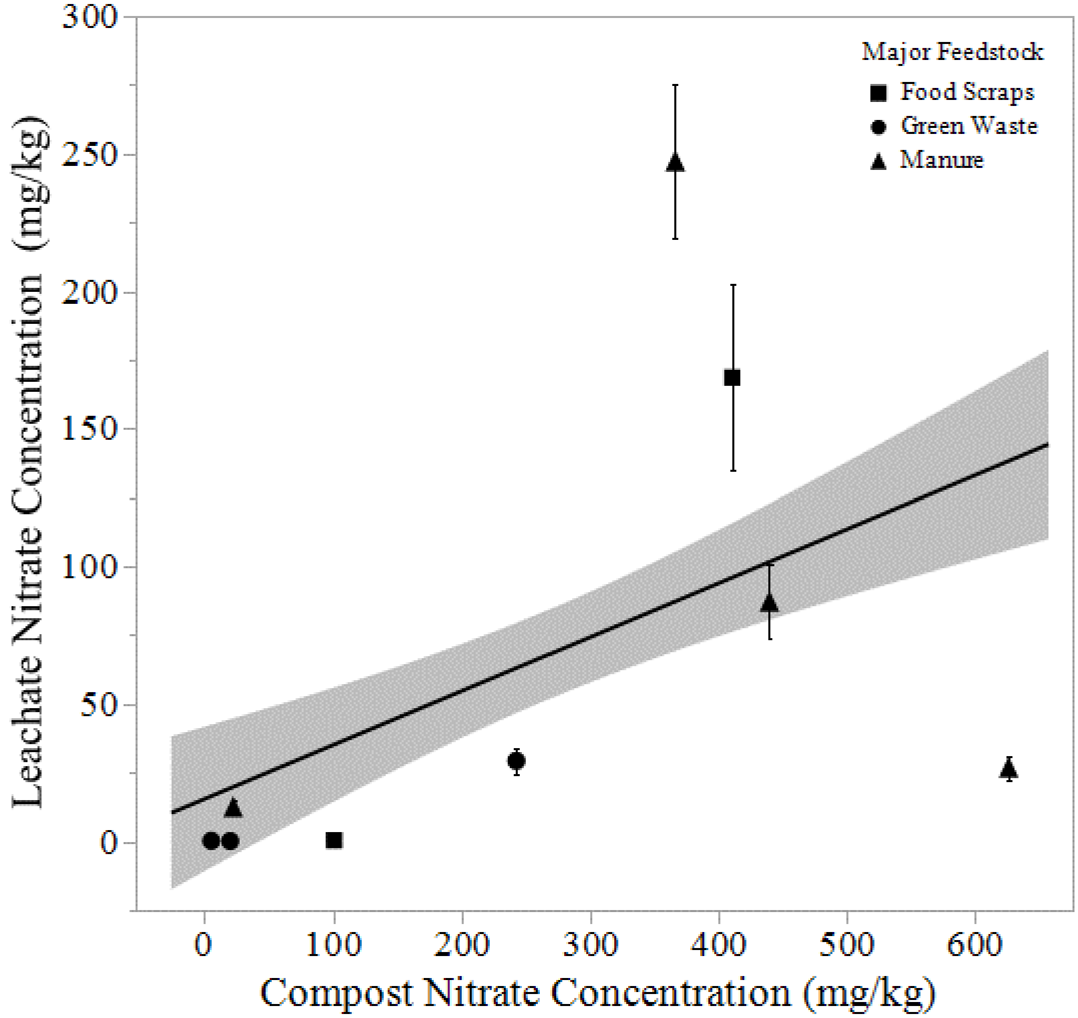


**Figure 9. Relationship between nitrate concentration in the composts alone** (100% compost). The manure-based compost in the lower left-hand corner is the WCE poultry manure compost which leached very little nitrate because the nitrogen in the compost was primarily in the form of ammonium. The black line represents the line of best fit; r2=0.145. The shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote standard error (n=6).

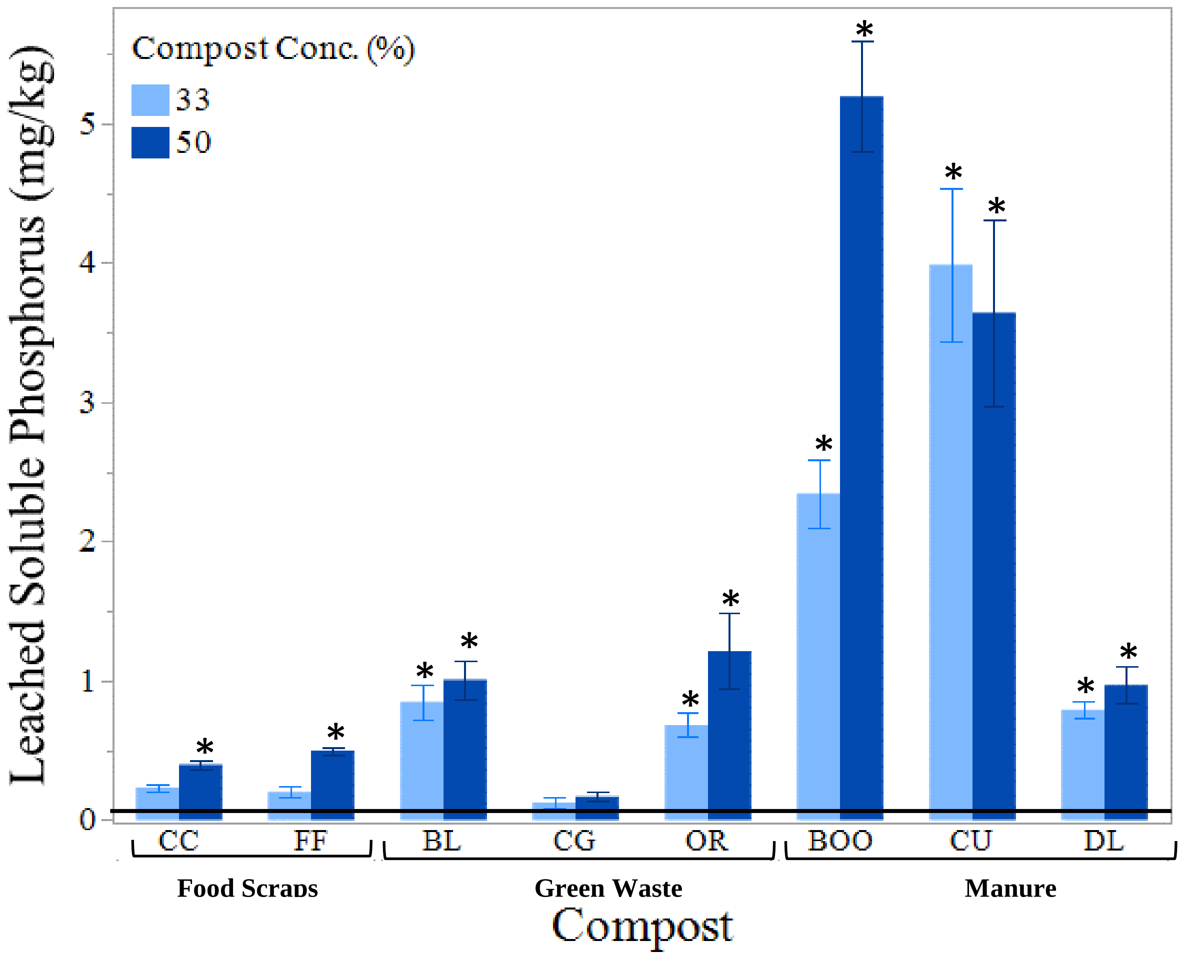


**Figure 10. Mean soluble phosphorous found in leachate by compost type.** Compost concentration of the growing media shown from light to dark (33% and 50%compost). WCE compost and 100% compost concentration was excluded. The horizontal solid black line indicates the mean soluble phosphorus found in the leachate from the control (soil) equaling 0.122 mg/kg. Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

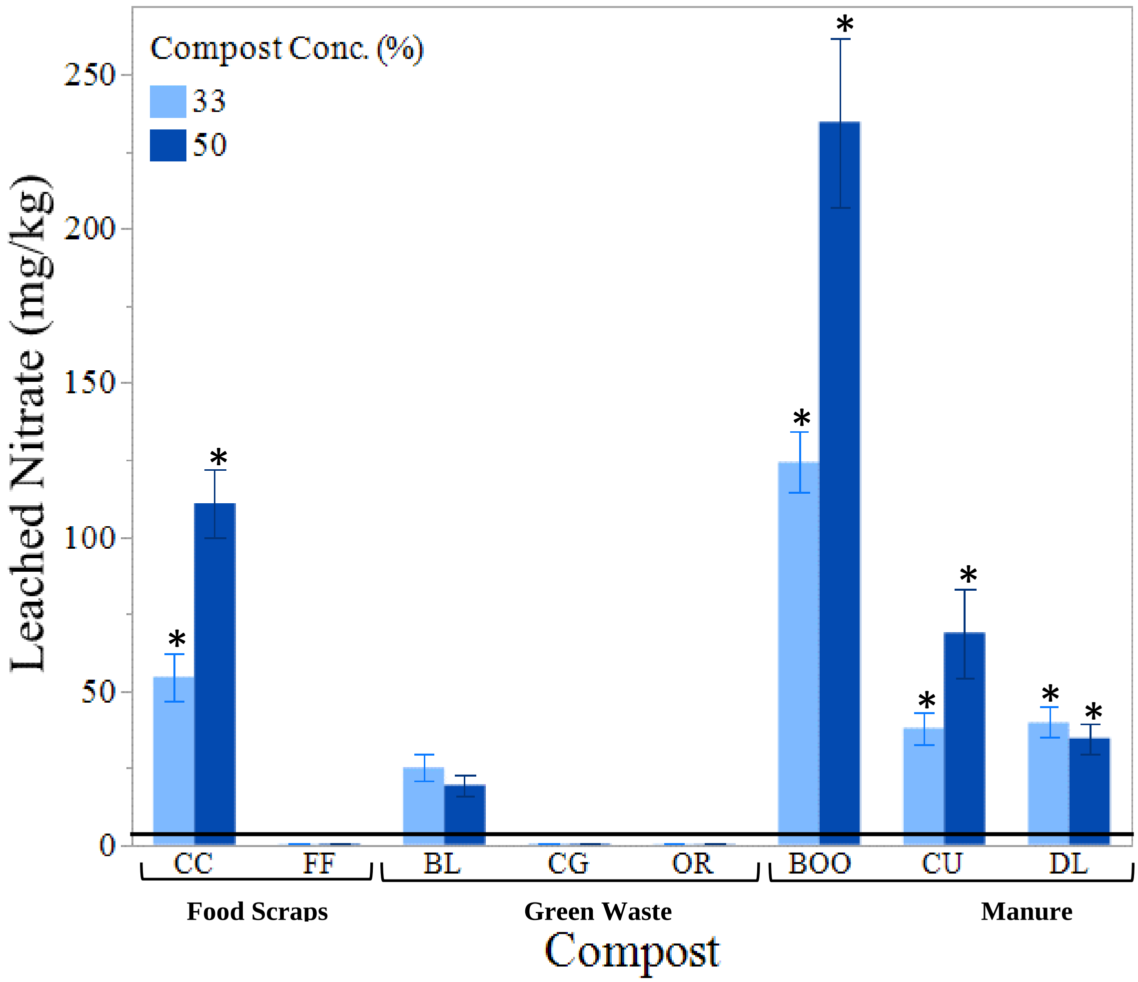


**Figure 11. Mean soluble Nitrate found in leachate by compost type.** Compost concentration of the growing media shown from light to dark (33% and 50% compost). WCE compost and 100% compost concentration was excluded. The horizontal solid black line indicates the mean nitrate found in the leachate from the control (soil) equaling 5.91 mg/kg. Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

## Discussion

*Testing Compost Quality*

The composts selected for this experiment were chosen to encompass a range of compost characteristics and feedstocks. We wanted to choose composts that were commercially available and made from common feedstock sources to best reflect what landscape managers would have access to. We used C:N ratio, OM and soluble salt content as qualities to narrow down our composts from 17 to 9, anticipating that those characteristics would be the strongest indicators of compost quality.

The initial compost quality parameters that must be met are those that indicate safety, such as contamination, maturity and traits like smell and presence of inert particles (trash). Those quality parameters apply to all compost regardless of their eventual use. Once those criteria are met, focus shifts to secondary quality parameters determined by the compost's end use (Rynk 2003; Tognetti et al. 2011). All nine composts used in the experiment tested well for maturity (above 6) when tested with a Solvita® Basic Field $CO_2$ test. However, the CG and WCE composts showed signs of immaturity. The CG (woodchips) and WCE (poultry manure) were included in the experiment to illustrate the extreme ends of the spectrum in terms of C:N and nutrient content. The woodchips were not, in fact, compost as they never underwent the composting process. The WCE poultry manure compost was composted but did not undergo a sufficient curing period. It was, instead, rapidly dried to prevent it from losing nutrients because it was intended to be marketed more as a fertilizer than as a compost. We believe its immaturity was one of the main reasons the bean plants failed to germinate in any of the WCE mixes.

As for the secondary quality parameters, the intended end-use was urban or disturbed soil remediation with 33-50% compost by volume. These soil to compost ratios had been found to improve soil health and reduce bulk density over time (Sax et al. 2017; Rivenshield & Bassuk, 2007). At these volumes the main compost characteristics of concern were C:N ratio, soluble salt content and nutrient content (N-P-K). Nutrient content is not often included in compost specifications, although it is generally included in compost laboratory testing. We found that if nutrient leaching is a concern, nutrient recommendations are important considerations when specifying a compost.

When testing compost, a recognized, consistent test protocol is critically important if one is to successfully adhere to written compost specifications and recommendations for use. We recommend compost producers and practitioners seek out labs that use TMECC, which was developed, with the assistance of many laboratories, by the U.S. Composting Council and modeled after the American Society for Testing and Materials (ASTM) (Thompson et al. 2002). Compost is an extremely variable product. Standardization of testing is a good way to mitigate uncertainty and increase universal understanding of a complex product that is often made from a mix of feedstocks and by a variety of processes.

*Soil Health*

All compost amendments carried out in this experiment improved soil health according to the Comprehensive Assessment of Soil Health completed at the Cornell Soil Health Lab (Moebius-Clune et al. 2016). These improvements included increased OM, active C, ACE (Autoclave Citrate Extractable) soil proteins, respiration and nutrient content. These results either directly indicated an increase in microbial activity or suggested a potential for increased microbial activity. OM%, a measure of the biomass-derived carbonaceous material in the soil, is the main energy source for microorganisms. Active C is the portion of that food source that is the most easily accessible for microorganisms. Soil proteins represent the large pool of organically bound N in the soil OM that can be mineralized by microbes and made available for plant uptake (Moebius-Clune et al. 2016). In our experiment, we measured an increase in OM from 2.2% in the control to as much as 8.85% with the addition of 50% BL compost and we found slight positive correlations between increased OM% and respiration, aggregate stability and available water holding capacity (AWHC). Treatments with 50% compost tended to show higher values for those characteristics than those with 33% compost.

Soil Respiration is a measure of carbon dioxide released from the soil due to microbial metabolic activity. The measurement of soil respiration integrates both abundance and activity of the microbial community. That activity includes nutrient cycling into and out of soil OM pools and N transformations like mineralization and nitrification. In our experiment respiration increased with the addition of all compost types at all concentrations. Increased OM, active C, and soil proteins, increases microbial activity. The greatest respiration in our experiment, was observed in the CG compost treatments (50% and 33%) at 1.98 and 1.44 mg $CO_2$, respectively. The CG compost did not display the highest OM%, protein content or active C content, however. We suspect the increased microbial activity might be due to the immature nature of the CG compost. There may have been more microbial activity because there was more potential for further decomposition. The 50% BL and 50% CC treatments displayed the highest OM% at 8.85% and 6.64%, respectively. They displayed the highest values for the ACE soil protein index at 20.26 (50% BL) and 23.40 (50% CC) as well as the highest active C contents at 1160.90 mg/kg (50% BL) and 951.82 mg/kg (50% CC). They correspondingly showed high levels of respiration at 1.15 mg $CO_2$ in the 50% BL treatment and 1.31 mg $CO_2$ in the 50% CC treatment.

That increased microbial activity then influenced soil aggregate stability, water retention, nutrient cycling, and cation exchange capacity (CEC) (Raviv 2005; Sax et al. 2017, Rivenshield & Bassuk, 2007; Sæbø and Ferrini 2006; Borken et al, 2004, Bernal et al., 1998, Lee et al., 2004, Lynch et al. 2005). Both 50% BL and 50% CC showed increased AWHC and increased aggregate stability. Compost can also inoculate soil that has been depleted of its microbial community. Pérez-Piqueres et al. (2006) found that incorporation of good quality composts may increase microbial biomass and enhance soil enzyme activity, although to what extent, depends on the compost and soil type. We believe it is likely some inoculation occurred in our experiment because respiration increased by a minimum of 81.25% and a maximum of 396.0% with the addition of compost (from 0.4 mg $CO_2$ in the soil alone to 0.72 mg $CO_2$ in the 33% OR and 1.98 mg $CO_2$ in the 50% CG) shortly after incorporation.

Aggregate stability increased by 19.4% to 97.4% with the addition of compost. Feedstock type did not seem to correlate with increased aggregate stability. Aggregate stability is greatly influenced by microbial activity as aggregates are held together by microbial products like polysaccharides, exudates and fungal hyphae. In our experiment certain treatments that displayed greater aggregate stability also showed greater plant growth such as BL, CU and BOO treatments (Figures 6 and 7). CG treatments also displayed a high percentage of aggregate stability, but still displayed poor growth, most likely because large pieces of woody material were mistaken for aggregates during laboratory testing.

Available water holding capacity either stayed the same or decreased slightly in the majority of our compost amended treatments. AWHC decreased by a maximum of 27% in the 33% WCE compost treatment. These results contradict most findings in the literature which cite increased AWHC with increased OM (Sax et al. 2017; Mikhailova et al. 2015; Chen et al. 2014).

Saxton and Rawls (2006) found that soil OM between 0.5% and 8.0% has been proven to increase AWHC in silt loam soils. However, despite OM% increasing for all eighteen of our treatments, only five displayed an increase in AWHC (33% and 50% BL, 50% CC, DL, BOO). The 50% BL (leaf compost) treatment displayed the greatest AWHC increase (68% up from the control), this treatment also showed the greatest OM%, 8.85%. The composts that displayed increases in AWHC (BOO, BL, CC) had larger percentages of fine particles (<2mm). BOO, BL, and CC composts contained 57.6%, 63.2% and 60.1% particles that were <2mm by dry weight, respectively (Figure 1). The treatments with the lowest AWHC were amended with OR, CU and CG composts which all displayed higher percentages of larger particles. OR, CU and CG composts contained 33.45%, 29.56% and 29.06% particles >1cm by dry weight (Figure 1). With larger pores, water most likely drained away by gravity as it could not be held by adhesion as it is in finer soils. We took our soil quality measurements immediately after incorporation. Over time, perhaps, once the compost could be broken down further by microorganisms, we might see different results, however further research is necessary to confirm this. In subsequent soil tests taken four and seven months later AWHC measurements fluctuated for all treatments (Appendix A).

Amending urban soil with compost is a simple solution that could immensely improve the health of urban landscapes. Not only does compost improve the biological, chemical and physical health of the soil, it contributes to maintenance of that health long-term. Sax et al. (2017) found increases in active C and aggregate stability over the course of their 12-year study and continual decreases in bulk density over that same time period. In urban areas, where landscapes get heavy use and often receive little regular fertilization, the long-term N availability that compost provides is particularly important (Alexander 2001; Diaz et al. 1993). Sæbø and

Ferrini (2006) suggest an annual top-application of compost because it serves a dual purpose, providing nutrients and OM and assisting with weed suppression.

Considering only soil health, it appears nearly any compost would improve compacted soil with low OM, low microbial activity and high bulk density. But it is important to consider plant health and nutrient retention as well.

*Plant Health*

Compost benefits plant growth indirectly, through remediating the soil and directly by providing nutrients immediately and continuously as it is transformed by microorganisms. However, because compost is a variable product, practitioners are often hesitant to utilize it as a nutrient source. Most compost specifications do not include nutrient recommendations, but we found nutrient content was an important consideration, not only for determining plant growth, but also to gauge to what extent nutrients might be lost after application. C:N ratio, soluble salt content and P and K content were the compost characteristics that appeared to have the greatest effect on plant growth.

The composts that performed the best in terms of plant health were BOO (cow manure-based compost), CU (horse manure and green waste compost), CC (food and green waste compost) and BL (leaf compost) (Figures 2-4). These four composts had C:N ratios ranging from 11.5 - 17.2. Their soluble salt content ranged from 1.9 - 3.4 mmhos/cm. Their phosphorous content ranged from 0.73% - 2.20% and their K content ranged from 1.4% - 4.4% (Table 1). These results indicated that compost quality is not necessarily feedstock dependent.

The C:N ratio range that proved optimal in this experiment was in line with what is often recommended in the literature for finished compost. According to Sikora and Schmidt (2001) the

C:N ratio considered optimal for compost is based on the C:N ratio of stable soil OM which generally falls between 10 and 15. Chatterjee et al. 2013 stated in their review that the ideal ratio for a compost used as a growing medium was 12–18 (CalRecycle, 2006).We found that a C:N ratio equal to or greater than 25 in the finished compost resulted in stunted growth and pale green color, most likely due to N immobilization which was confirmed by Brady and Weil (1999). Because we did not include a compost in our experiment with a C:N ratio between 17 and 25 we were unable to determine a maximum C:N ratio that would still allow enough available N for plant growth. Sikora and Szmidt (2001) and Sullivan et al. (2003) found that in composts with a C:N of 20 or less, 5 to 15% of total N became plant-available during the first year after application. Because we chose beans as our bioassay species, we also must consider the effects of nodulation, which occurred in all treatments over the course of the bioassay. Despite nodulation, many plants exhibited yellow leaves and stunted growth suggesting that nodulation did not make up for low N in some of the treatments.

Mupondi et al. (2006) and Warman and Termeer (1996) both utilized bioassays in the greenhouse to evaluate the use of compost mixes on plant germination and growth. Both found that a mix of nutrient-rich material composted with a carboniferous material resulted in the strongest plant growth. The compost that performed the best for Mupondi et al. was a pine bark and goat manure blend with a C:N ratio of 16, which is in line with our findings. Mupondi et al. found that composted pine bark alone immobilized N and resulted in stunted plant growth, much like our CG woodchips. Warman and Termeer saw plant growth decline when greater than 50% compost was utilized in the growing media whereas many of our bioassay plants thrived in up to 100% manure-based compost. Nutrient levels of the compost and nutrient requirements of the desired plants or crops will vary, but the literature seems to agree that a combination of nutrient-rich and carboniferous feedstocks provide for the best growing media.

A low level of salinity is important in compost because it indicates the presence of nutrients in the form of cations and anions that are required for plant growth. High salinity, however, can inhibit germination and plant growth (Zmora-Nahum et al. 2007). The treatments in this experiment with soluble salt content below 0.5 mmhos/cm resulted in poor growth and greenness, particularly when low salinity coincided with high C:N. We did not have sufficient data to offer a maximum safe soluble salt content based on our bioassay because we lacked a treatment with a soluble salt content between 3.4 mmhos/cm and 17.6 mmhos/cm which inhibited germination completely. The composts that performed the best in our study had soluble salt contents from 1.9 - 3.4 mmhos/cm. Much depends on plant selection and in urban landscapes the use of salt-tolerant plants is encouraged due to regular salting of roads and walkways in cities located in regions with cold winters. Much of the literature agrees that compost amendments that increase the soil soluble salt levels higher than 4 mmhos/cm can pose a risk to healthy plant growth (Gollardo & Nogales 1987), but many standard compost specifications set the maximum electrical conductivity levels as high as 10 mmhos/cm (USCC 2005).

We found strong positive correlations between P and K content and plant growth. This is not surprising because P and K are vital macronutrients. P is necessary for various plant processes such as photosynthesis, respiration, N fixation, root development, maturation, flowering, fruiting, and seed production (Ketterings et al. 2003). We used the Modified Morgan method (McIntosh 1969) of phosphorus extraction to measure available P in our growing media. This method tends to be less sensitive then other extraction methods such as Mehlich III, Bray-Kurtz P1 and Olsen (Pote et al. 1999; Penn State 2001). However, we still found extremely high levels of Modified Morgan phosphorus (MMP) in our treatments. The recommended 33% treatment of the composts that showed the best performance (BOO, CU, CC, BL) showed a range of MMP from 49.0 – 130.63 mg/kg MMP. Jokela et al. (1998) found the optimal range of MMP for field crops to be from 4.0 to 7.0 mg/kg. 4.0 mg/kg MMP was cited as the critical value and additions of P fertilizer were recommended for soil with MMP levels up to 7.0 mg/kg. In their paper, Jokela et al. characterized soil with MMP above 20 mg/kg as excessive. All but three of our treatments (30% and 50% CG and 33% OR) exceeded 20 mg/kg MMP. Consequences of excess available P are far reaching, and P can remain in the soil far longer than N. For this reason, compost testing, site analysis and thoughtful timing of compost amendments are important considerations. Although the soil remediation method we are testing calls for 33% compost by volume, it may be wise to use 25%, if P leaching is a concern on the intended site. Amendments of 25% compost by volume have been shown to improve bulk density in compacted sandy loam soil (Rivenshield and Bassuk 2007).

Our results displayed both the positive and negative impacts compost amendment can have on plant growth. Type of compost and amount of amendment will depend on the needs of the plants, but compost is undoubtedly a sustainable, affordable nutrient source for plants in the landscape.

*Nutrient Leaching*

Compost is less susceptible to nutrient losses during large rain events than inorganic fertilizers that are completely soluble, but the soluble nutrients in compost are still of concern (Hurley et al. 2017). Site and soil assessment are important steps to take prior to compost amendment, as are compost laboratory tests.

In a drier area with deeper soil, composts made with a mixture of manure and some carboniferous bulking agent could be used safely. However, on a site with well-drained soil, particularly moist conditions, or a high risk of runoff, manure-based compost is most likely too high in P and will result in nutrient pollution.  Hurley et al. (2017) suggest that ≤0.2% P be the definition of low P compost. Low P composts are primarily derived from yard or green waste, as opposed to composts derived from food scraps, manure, or biosolids (Hinman 2009). The CG woodchips contained the lowest concentration of P of the composts we tested, with 0.22%. All non-manure-based composts used contained <0.9% P. Finding a compost with ≤0.2% P might be a challenge for compost users if leaching is a concern.

Timing of compost incorporation is crucial, particularly when compost amendment is occurring before the landscape is installed. It would be unwise to leave the amended soil unplanted for long stretches of time because available nutrients will be lost without established plant uptake. Most compost specifications do not include N content, outside of the C:N ratio, and P content is generally omitted as well. When incorporating compost into soil at such large volumes it is necessary to include nutrient ranges in specifications to make informed management decisions.

Borken et al. (2004) found composts rich in N can cause excessive nitrate leaching during the first one to two years after application. In their experiment, Borken et al. measured N leaching in a forested area and observed that the mineral soils acted as a significant sink for NO−3 and dissolved organic N. This experiment confirmed that where there was deeper soil to catch nutrients as they leach, N and P-rich composts may be safer to use.

Amlinger et al. (2003) discouraged the use of very large amounts of compost as a soil amendment, especially in well-drained soils. Nutrient leaching from compost-amended soils could exacerbate existing eutrophication problems, which threaten the health of coastal and freshwater systems (Carpenter et al. 1998; Hurley et al. 2017). This danger is elevated when composts are applied in late autumn and winter when plants are not actively growing. Spring is the best time to apply compost, when plants can take up dissolved nutrients, so they don't end up polluting groundwater (Amlinger et al. 2003).

We found a direct correlation between the concentration of MMP in the media and the concentration of soluble reactive phosphorus (SRP) found in the leachate ($r^2$=0.79). According to Pote et al. (1996) the soil P extraction test that will best predict SRP loss depends on soil type. In their study using Captina silt loam, they found the distilled water and acidified ammonium oxalate (Sheldrick, 1984) extraction methods were the most accurate indicators of SRP in the leachate, although all the methods they used showed statistically significant correlations. In 1999, Pote et al. came out with another study using three more ultisols to see if different methods would be more accurate with different soil types. They found several tests were good predictors (with an $r^2 > 0.90$) for all three soils, including Mehlich III, Modified Morgan, Bray-Kurtz P1 and Distilled Water. This confirms our results that MMP in the compost would be a good indicator of potential P leaching and a P extraction would be a valuable addition to regular compost laboratory analysis and specification.

We did not find a compost measurement that correlated strongly with nitrate leaching on its own. We know that a higher C:N ratio results in increased N immobilization and therefore reduces the threat of leaching. Increased C:N was negatively correlated with nitrate concentration in the leachate. However, the $r^2$ was only 0.079. We assessed this relationship based solely on the 100% compost treatment, because we did not test for C:N in the soil mixes. Nitrate concentration in the compost was only slightly positively correlated with nitrate concentration in the leachate with an $r^2$ of 0.145. We believe that a larger sample size could result in stronger correlations, however, more research is necessary to better predict likelihood of nitrate leaching from compost.

**Conclusion**

Compost is a valuable renewable resource for rebuilding depleted soils, reducing compaction and reinvigorating disturbed landscapes. Our objective was to identify a range of acceptable compost characteristics that could be used for soil remediation in the urban landscape. We analyzed composts made from combinations of three main feedstocks, animal manure, green waste and food scraps. We wanted to take into account soil health, plant health and the potential of nutrient leaching in our recommendations. Although all nine composts used in this experiment improved soil health, the green waste composts received the highest scores from the Cornell Soil Health Lab. We also found that the higher compost concentration (50%) tended to improve soil characteristics more than the lower concentration (33%).

We found very different results when we evaluated plant growth. The nutrient rich composts made from cow and horse manure and food scraps produced the largest, greenest plants. The woody composts were detrimental to growth, immobilizing all N that might otherwise be available to the plant. However, those nutrient rich composts that boosted plant growth, leached high levels of nitrate and SRP.

Taking all the information collected from our research and experimentation into consideration we came up with recommended ranges for the ideal compost for urban soil remediation. The main concerns were C:N, P% and soluble salt content. We found the ideal ranges were 10 – 20 for C:N ratio, 0.2% – 0.9% P and a soluble salt content between 1.0 and 3.5 mmhos/cm (Appendix B). Composts that exhibit these characteristics tend to be combinations of several feedstocks, some richer in N and P like manure, food waste or grass clippings and others richer in carboniferous material. Moreover, these levels produced good plant growth with minimal nutrient leaching. There are a wide variety of composts available for growers and landscapers with distinct nutrient contents, nutrient leaching potential, bacterial community composition, and other qualities that vary by the feedstocks used and the process through which the compost was produced (Confesor et al. 2009; Chatterjee et al. 2013). It is important to test compost qualities using a standard testing protocol such as the TMECC protocol.

When using compost as a soil amendment the safest approach is to understand site conditions soil type and drainage, which will help improve plant growth and minimize nutrient leaching. As we learn more about compost properties and streamline and standardize testing and regulations, we believe the knowledgeable incorporation of compost will play a critical role in improving soil and plant growth in disturbed urban soils.

**References**

Alexander, R. (2001). Compost utilization in landscapes. *Compost utilization in horticultural cropping systems*, 151-175.

Amlinger, F., Götz, B., Dreher, P., Geszti, J., & Weissteiner, C. (2003). Nitrogen in biowaste and yard waste compost: Dynamics of mobilisation and availability—a review. *European Journal of Soil Biology*, *39*(3), 107–116. https://doi.org/10.1016/S1164-5563(03)00026-8

B.N. Moebius, H.M. van Es, R.R. Schindelbeck, O.J. Idowu, J.E. Thies, D.J. Clune. 2007. Evaluation of Laboratory-Measured Soil Physical Properties as Indicators of Soil Quality. Soil Science Vol. 172, No. 11, pp. 895-910.

Bernal M, Navarro A, Sánchez-Monedero M, Roig A, Cegarra J (1998) Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. Soil Biol Biochem 30(3):305–313

Borken, W., Xu, X.J., Beese, F., 2004. Ammonium, nitrate and dissolved organic nitrogen in seepage water as affected by compost amendments to European beech, Norway spruce and Scots pine forests. Plant and Soil 258, 121–134

Brady, N. C., & Weil, R. R. (1999). The nature and properties of soil 12th ed. *Mac. Pub. Com. New York*, 625-640.

Bugbee, G. J. (2002). Growth of ornamental plants in container media amended with biosolids compost. *Compost Science & Utilization; Abingdon*, *10*(2), 92.

CalRecycle 2006. Organic Materials Management—Compost—What Is It? http:// www.calrecycle.ca.gov/organics/compostmulch/CompostIs.htm, accessed on April 26, 2019.

Carpenter,S.R.,Caraco,N.F.,Correll,D.L.,Howarth,R.W.,Sharpley,A. N., and Smith, V. H. (1998). “Nonpoint pollution of surface waters phosphorus and nitrogen.” Ecol. Appl., 8(3), 559–568.

Chatterjee,N.,Flury,M.,Hinman,C.,andCogger,C.G.(2013).“Chemical and physical characteristics of compost leachates: A review.” ⟨http:// www.wsdot.wa.gov/research/reports/fullreports/819.1.pdf⟩

Chen, Y., Day, S. D., Wick, A. F., & McGuire, K. J. (2014). Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. *Science of The Total Environment*, *494–495*, 329–336. https://doi.org/10.1016/j.scitotenv.2014.06.099

Cogger, C. G. (2005). Potential Compost Benefits for Restoration Of Soils Disturbed by Urban Development. *Compost Science & Utilization; Abingdon*, *13*(4), 243–251.

Confesor, R. B., Jr., Hamlett, J. M., Shannon, R. D., and Graves, R. E. (2009). “Potential pollutants from farm, food and yard waste composts at differing ages: Leaching potential of nutrients under column experiments.” Compos. Sci. Util., 17(1), 6–17.

Craul, P. J. (1999). *Urban Soils: Applications and Practices*. John Wiley & Sons.

De Bertoldi, M., Ferranti, M. P., L'Hermite, P., & Zucconi, F. (1987). Compost: production, quality and use. *Elsevier Applied Science. London,(41145)*, 853.

Hurley Stephanie, Shrestha Paliza, & Cording Amanda. (2017). Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. *Journal of Sustainable Water in the Built Environment*, *3*(3), 04017006. https://doi.org/10.1061/JSWBAY.0000821

Jaber, F.H., S. Shukla, P.J. Stoffella, T.A. Obreza, and E.A. Hanlon. 2005. Impact of organic amendments on groundwater nitrogen concentrations for sandy and calcareous soils. Compost Sci. Util. 13:194-202.

Jokela, W. E., Magdoff, F. R., & Durieux, R. P. (1998). Improved phosphorus recommendations using modified Morgan phosphorus and aluminum soil tests. *Communications in Soil Science and Plant Analysis*, *29*(11–14), 1739–1749. https://doi.org/10.1080/00103629809370064

Kandeler, E., and H. Gerber. 1988. Short-term assay of soil urease activity using colorimetric determination of ammonium. Biol. Fertil. Soils 6:68–72.

Ketterings, Q.M., K.J. Czymmek and S.D. Klausner (2003). Phosphorus guidelines for Field Crops in New York. Second Release. Department of Crop and Soil Sciences Extension Series E03-15. Cornell University, Ithaca NY. 35 pages.

Lee, J. J., Park, R. D., Kim, Y. W., Shim, J. H., Chae, D. H., Rim, Y. S., ... & Kim, K. Y. (2004). Effect of food waste compost on microbial population, soil enzyme activity and lettuce growth. *Bioresource Technology*, *93*(1), 21-28.

Li, G.; Sun, G.-X.; Ren, Y.; Luo, X.-S.; Zhu, Y.-G. Urban soil and human health: a review. European Journal of Soil Science 69, 196–215.

Loper, S. J., Shober, A. L., Wiese, C., Denny, G. C., & Stanley, C. D. (2013). Nutrient Leaching during Establishment of Simulated Residential Landscapes. *Journal of Environmental Quality; Madison*, *42*(1), 260–270.

Lynch, D. H., Voroney, R. P., & Warman, P. R. (2005). Soil Physical Properties and Organic Matter Fractions Under Forages Receiving Composts, Manure or Fertilizer. *Compost Science & Utilization; Abingdon*, *13*(4), 252–261.

McIntosh, J. L. (1969). Bray and Morgan Soil Extractants Modified for Testing Acid Soils from Different Parent Materials 1. *Agronomy Journal*, *61*(2), 259-265.

McPhillips Lauren, Goodale Christine, & Walter M. Todd. (2018). Nutrient Leaching and Greenhouse Gas Emissions in Grassed Detention and Bioretention Stormwater Basins. *Journal of Sustainable Water in the Built Environment*, *4*(1), 04017014. https://doi.org/10.1061/JSWBAY.0000837

Miranda, K.M., M.G. Espey, and D.A. Wink. 2001. A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. Nitric Oxide 5:62–71.

Moebius-Clune, B. N., Moebius-Clune, D. J., Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., & Ristow, A. J. (2016). Comprehensive assessment of soil health: The Cornell Framework Manual, Edition 3.1, Cornell Univ., Ithaca, NY.

Mupondi, L. T., Mnkeni, P. N. S., & Brutsch, M. O. (2006). Evaluation of pine bark or pine bark with goat manure or sewage sludge cocomposts as growing media for vegetable seedlings. *Compost Science & Utilization*, *14*(4), 238-243. Retrieved from https://search.proquest.com/docview/214883389?accountid=10267

Mupondi, L. T., Mnkeni, P. N. S., & Brutsch, M. O. (2006). The Effects of Goat Manure, Sewage Sludge And Effective Microorganisms on the Composting of Pine Bark. *Compost Science & Utilization; Abingdon*, *14*(3), 201–210.

Natural Resource, Agriculture, and Engineering Service (NRAES). 1992. On-farm composting, edited by R. Rynk. Ithaca, USA, NRAES Cooperative Extension.

Pérez-Piqueres, A., Edel-Hermann, V., Alabouvette, C., & Steinberg, C. (2006). Response of soil microbial communities to compost amendments. *Soil Biology and Biochemistry*, *38*(3), 460–470. https://doi.org/10.1016/j.soilbio.2005.05.025

Pote, D. H., Daniel, T. C., Moore, P. A., Nichols, D. J., Sharpley, A. N., & Edwards, D. R. (1996). Relating Extractable Soil Phosphorus to Phosphorus Losses in Runoff. *Soil Science Society of America Journal*, *60*(3), 855–859. https://doi.org/10.2136/sssaj1996.03615995006000030025x

Pote, D. H., Daniel, T. C., Nichols, D. J., Sharpley, A. N., & al, et. (1999). Relationship between phosphorus levels in three ultisols and phosphorus concentrations in runoff. *Journal of Environmental Quality; Madison*, *28*(1), 170.

Raviv, M. (2005). Production of High-quality Composts for Horticultural Purposes: A Mini-review. *HortTechnology*, *15*(1), 52–57.

Reynolds, W. D., G.C. Topp. 2008. Soil water desorption and imbibition: tension and pressure techniques. Soil sampling and methods of analysis. 2nd ed. CRC Press, Boca Raton, FL, 981-997.

Rivenshield, A., Bassuk, N.L., 2007. Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboric. Urban For. 33, 140.

Sax, M. S., Bassuk, N., van Es, H., & Rakow, D. (2017). Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. *Urban Forestry & Urban Greening*, *24*, 149–156. https://doi.org/10.1016/j.ufug.2017.03.023

Sæbø, A., & Ferrini, F. (2006). The use of compost in urban green areas – A review for practical application. *Urban Forestry & Urban Greening*, *4*(3), 159–169. https://doi.org/10.1016/j.ufug.2006.01.003

Thompson, W., Leege, P., Millner, P., & Watson, M. E. (2002). Test methods for the examination of compost and composting (TMECC). *Reston, VA, USA: Composting Council*.

USCC. 2005. Landscape Architecture/Design Specifications for Compost Use. https://compostingcouncil.org/wp-content/plugins/wp-pdfupload/pdf/32/Landscape-Architecture-Specs.pdf

Warman, P. R., & Termeer, W. C. (1996). Composting and evaluation of racetrack manure, grass clippings and sewage sludge. *Bioresource Technology*, *55*(2), 95–101. https://doi.org/10.1016/0960-8524(95)00110-7

Wright S.F., A. Upadhyaya. 1996. Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Science 161: 575-586.

Weil, R., K.R. Islam, M.A. Stine, J.B. Gruver, S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simple method for laboratory and field use. Amer. J. Alternative Agric. 18(1):3-17.

Zibilske L. 1994. Carbon mineralization. Methods of Soil Analysis: Part 2—Microbiological and Biochemical Properties. Soil Science Society of America, Madison, WI, pp. 835-863.

## Appendix A

| FeedStock | ID | AWHC | Aggregate Stability (%) | OM (%) | Respiration (mg) | Active C (mg/kg) | P (mg/kg) | Soluble Salts (mmho/cm) |
|---|---|---|---|---|---|---|---|---|
| SOIL | **S** | **0.220** | **34.700** | **2.200** | **0.400** | **317.000** | **5.300** | **0.03** |
| | **S** | **0.182259** | **40.86598285** | **2.66** | **0.290825394** | **310.977** | **4** | **0.22** |
| | **S** | **0.167851** | **67.74611792** | **2.73** | **0.566045523** | **359.271** | **6.3** | **0.25** |
| GREEN WASTE | **CG50** | 0.197 | 63.584 | 4.802 | 1.984 | 753.366 | 18.845 | 0.417 |
| | **CG50** | 0.241622 | 56.34163867 | 5.69 | 1.390287249 | 728.7686 | 20.3 | 0.69 |
| | **CG50** | 0.218076 | 81.81785767 | 6.65 | 1.715160494 | 808.9675 | 22.8 | 0.62 |
| | **CG33** | 0.204 | 60.122 | 3.743 | 1.441 | 562.003 | 12.318 | 0.245 |
| | **CG33** | 0.203937 | 43.37438292 | 4.47 | 1.134928367 | 617.963 | 10.6 | 0.33 |
| | **CG33** | 0.160552 | 77.81885571 | 3.88 | 1.232815938 | 652.0966 | 12.4 | 0.4 |
| | **OR50** | 0.220 | 48.680 | 4.515 | 0.902 | 732.103 | 22.591 | 0.247 |
| | **OR50** | 0.30239 | 55.22164504 | 6.56 | 1.604504979 | 1028.794 | 27.1 | 0.40 |
| | **OR50** | 0.210668 | 78.93470812 | 7.31 | 1.353402077 | 869.9728 | 27.8 | 0.67 |
| | **OR33** | 0.186 | 50.402 | 3.146 | 0.725 | 553.144 | 11.601 | 0.204 |
| | **OR33** | 0.205309 | 47.41161172 | 4.61 | 0.758983345 | 594.3487 | 11.5 | 0.45 |
| | **OR33** | 0.191326 | 76.35512668 | 4.97 | 1.225722636 | 700.9009 | 13.9 | 0.39 |
| | **BL50** | 0.367 | 62.907 | 8.848 | 1.147 | 1160.897 | 130.815 | 0.881 |
| | **BL50** | 0.273607 | 50.25969207 | 9.69 | 0.838428331 | 1168.281 | 109.2 | 0.77 |
| | **BL50** | 0.301573 | 68.04675314 | 10.78 | 1.275375752 | 1147.111 | 95.5 | 0.6 |
| | **BL33** | 0.243 | 57.139 | 4.967 | 0.831 | 918.150 | 49.004 | 0.510 |
| | **BL33** | 0.295419 | 41.16655195 | 6.17 | 0.689468983 | 942.9558 | 46.3 | 0.64 |
| | **BL33** | 0.192156 | 70.60044324 | 7.32 | 0.785937894 | 922.2631 | 40.5 | 0.56 |
| FOOD WASTE | **FF50** | 0.211 | 49.885 | 5.382 | 1.292 | 827.785 | 46.092 | 0.154 |
| | **FF50** | 0.222968 | 57.6849874 | 7.77 | 1.071088646 | 779.6302 | 67.6 | 0.57 |
| | **FF50** | 0.187735 | 83.87002372 | 6.43 | 1.133509706 | 822.9116 | 54.9 | 0.45 |
| | **FF33** | 0.199 | 50.134 | 3.571 | 0.994 | 629.334 | 24.886 | 0.126 |
| | **FF33** | 0.225886 | 56.23144388 | 5.02 | 0.815729764 | 621.596 | 28.7 | 0.40 |
| | **FF33** | 0.188475 | 80.54465593 | 5.04 | 1.005830265 | 660.8117 | 29.9 | 0.45 |
| | **CC50** | 0.237 | 51.487 | 6.636 | 1.310 | 951.816 | 126.332 | 1.115 |
| | **CC50** | 0.194638 | 50.3302674 | 7.77 | 0.822823066 | 814.1434 | 166.3 | 1.85 |
| | **CC50** | 0.187059 | 72.80194389 | 7.1 | 1.090949893 | 871.7158 | 140.3 | 0.75 |
| | **CC33** | 0.201 | 57.883 | 4.555 | 1.126 | 758.681 | 69.081 | 0.756 |
| | **CC33** | 0.160461 | 49.14089631 | 5.62 | 0.595837393 | 588.8993 | 97 | 1.11 |
| | **CC33** | 0.168135 | 76.20148179 | 4.21 | 0.800124499 | 704.3869 | 64.5 | 0.63 |
| MANURE | **DL50** | 0.266 | 41.428 | 5.742 | 1.317 | 707.297 | 59.616 | 0.543 |
| | **DL50** | 0.205384 | 73.65878794 | 6.67 | 1.170394878 | 872.2709 | 71 | 0.85 |
| | **DL50** | 0.232077 | 86.61342925 | 7.5 | 1.403055193 | 1047.76 | 58.3 | 0.39 |
| | **DL33** | 0.202 | 48.989 | 3.701 | 0.952 | 487.584 | 21.113 | 0.353 |
| | **DL33** | 0.235511 | 56.30569855 | 6.16 | 0.978875716 | 632.4949 | 27 | 0.55 |
| | **DL33** | 0.200712 | 86.26090893 | 5.24 | 1.473988216 | 801.9955 | 20.6 | 0.36 |
| | **CU50** | 0.193 | 64.051 | 5.236 | 1.083 | 570.862 | 149.407 | 0.816 |
| | **CU50** | 0.306623 | 58.34948641 | 6.21 | 0.851196275 | 748.75 | 133.3 | 0.69 |
| | **CU50** | 0.248328 | 75.34150631 | 7.3 | 1.062576683 | 749.7052 | 163.3 | 0.57 |
| | **CU33** | 0.181 | 68.502 | 4.070 | 0.945 | 487.584 | 68.362 | 0.568 |
| | **CU33** | 0.274568 | 32.72808756 | 4.98 | 0.645490509 | 648.8433 | 66.8 | 0.61 |
| | **CU33** | 0.204133 | 67.49594259 | 4.16 | 0.984550358 | 653.8396 | 58.4 | 0.43 |
| | **BOO50** | 0.244 | 58.535 | 5.397 | 0.984 | 664.772 | 180.137 | 0.901 |
| | **BOO50** | 0.202462 | 65.40071099 | 9.39 | 0.746215401 | 799.892 | 355.7 | 1.18 |
| | **BOO50** | 0.151099 | 80.03374771 | 8.13 | 0.941990544 | 697.4149 | 285.7 | 0.89 |
| | **B0033** | 0.189 | 60.379 | 4.309 | 0.849 | 579.722 | 130.627 | 0.812 |
| | **B0033** | 0.163651 | 56.75906494 | 5.8 | 0.71074889 | 642.5218 | 113.1 | 0.79 |
| | **B0033** | 0.151565 | 78.56127541 | 5.03 | 0.693724964 | 570.1752 | 102.8 | 0.51 |

**Appendix A. Unamended and amended soil characteristics for all three samples taken during the bioassay.** The soil used in all mixes is an Arkport sandy loam. Tests followed the *Comprehensive assessment of soil health: the Cornell framework manual* protocol by Moebius-Clune.

## **Appendix B:** Scoop and Dump Compost Specification (For planting beds)

### SCOOP AND DUMP METHOD

After critical root zone protection has occurred, grade and remove all plants and debris from the surface. Spread 6 inches of compost over the surface of the soil. Loosen the soil to depth of 18 - 24 inches, using a backhoe or excavator to dig into the soil through the compost. Lift and then drop the loosened soil immediately back into the hole. The bucket then moves to the adjacent soil and repeats the process until the entire area indicated has been loosened. Scoop and Dump so that the backhoe is working away from soil that has already been amended.

### COMPOST SPECIFICATION

Compost for amending planting media shall be a stable, mature, humus-like material produced from the aerobic decomposition and curing of organic biomass residues. The compost shall be a dark brown to black color and be capable of supporting plant growth with appropriate management practices in conjunction with addition of fertilizer and other amendments as applicable, with no visible free water or dust, with no unpleasant odor, and meeting the following criteria as reported by laboratory tests. Recommended test methodologies are provided in Test Methods for the Examination of Composting and Compost (TMECC) from the United States Composting Council (USCC).

1. The ratio of carbon to nitrogen shall be in the range of 10:1 to 20:1.
2. Stability shall be assessed using the Solvita® procedure or the Carbon dioxide evolution rate procedure described in the Respirometry section of the TMECC (05.08-B). The carbon dioxide evolution rate must be <8 mg $CO_2$-C per g OM per day. The Solvita® protocol is specified by the Solvita® manual (version 3.5). The compost must achieve a maturity index of 6 or more. Woods End Research Laboratory, Mt. Vernon, Maine, or approved equal shall conduct stability tests.
3. Maturity shall be assessed with a biological assay procedure described in TMECC 05.09-A. Seed emergence and seed vigor shall be ≥80% relative to a positive control.
4. Chemical contaminants shall meet the US EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3 levels. (Arsenic = 41ppm, Cadmium = 39ppm, Copper = 1,500ppm, Lead = 300ppm, Mercury = 17ppm, Molybdenum = 75ppm, Nickel = 420ppm, Selenium = 100ppm, Zinc = 2,800ppm)
5. Biological contaminants shall meet the US EPA Class A standard, 40 CFR § 503.32(a) levels (Salmonella <3 MPN/4grams of total solids or Fecal Coliform <1000 MPN/gram of total solids)
6. Organic Matter (OM) content shall be at least 24 percent (dry weight). One hundred percent of the material shall pass a 1.0 inch (2.6 cm) screen. Debris such as metal, glass, plastic, wood (other than residual chips), asphalt or masonry shall not be visible and shall not exceed one percent dry weight. Organic content shall be determined by weight loss on ignition for particles passing a number 10 sieve as follows. A 50-cc

sub-sample of the screened and mixed compost is ground to pass the number 60 sieve. Two to three grams (0.001g) of ground sample, dried to a constant weight at 105 degrees C is placed into a muffle furnace. The temperature is slowly raised (SC/minute) to 450C and maintained for three hours. The sample is removed to an oven to equilibrate at 105C and the weight is taken. Organic matter is calculated as loss on ignition.

7. pH: The pH shall be between 6.0 to 8.2 as determined from a 1:1 soil-distilled water suspension using a glass electrode pH meter American Society of Agronomy *Methods of Soil Analysis*, Part 2, 1986.

8. Salinity: Electrical conductivity of a one to five soil to water ratio slurry extract shall not be lower than 1.0 mmhos/cm or exceed 3.5 mmhos/cm (dS/m) for use in blending.

9. Phosphorus: Percent $P_2O_5$ shall be below 1.0% dry matter; preferably lower if C:N ratio is also low or if leaching is a concern.

10. The compost shall be screened to 1.0 inch (2.6 cm) maximum particle size and shall contain not more that 3 percent material finer than 0.002mm as determined by hydrometer test on ashed material.

11. Nutrient content shall be determined by the Cornell University Soil Testing Laboratory or equivalent laboratory and utilized to evaluate soil required amendments for the mixed soils. Chemical analysis shall be undertaken for Nitrate Nitrogen, Ammonium Nitrogen, Phosphorus, Potassium, Calcium, Aluminum, Magnesium, Iron, Manganese, Lead, Soluble Salts, Cation Exchange Capacity, soil reaction (pH), and buffer pH

| Parameters | Recommended Ranges | Units | References |
|---|---|---|---|
| pH | 6.0 - 8.2 | - | Heyman 2019 |
| C:N | 10 - 20 | ratio | Sullivan et al. 2018; Sikora & Schmidt 2001; Chaterjee et al. 2013 |
| Organic Matter | >24 | % dry matter | Heyman 2019 |
| Soluble Salts | 1.0 - 3.5 | mmhos/cm | Reddy & Crohn 2012; Heyman 2019 |
| Total N | 0.5 - 3.5 | % dry matter | The Pennsylvania State University AASL |
| NO3-N | 100 - 1,000 | mg/kg | Sullivan et al. 2018 |
| NH4-N | <500 | mg/kg | Sullivan et al. 2018 |
| NH4:NO3 | <10 | - | Sullivan et al. 2018 |
| P2O5 | <1.0 | % dry matter | Schwarz & Bonhotal 2017; Sullivan et al. 2018; Heyman 2019 |
| K20 | 1.0 - 3.0 | % dry matter | Schwarz & Bonhotal 2017; Heyman 2019 |
| Particle Size | 100% passing through 3 cm sieve<br>85% passing through 2 cm sieve<br>40-60% passing through 2mm sieve | % dry matter | Heyman 2019 |

## RECOMMENDATIONS TO REDUCE NUTRIENT LEACHING BASED ON SITE ANALYSIS

When incorporating large quantities of compost at once, loss of soluble nutrients by leaching may be a concern. Compost is far less susceptible to nutrient losses than inorganic fertilizers that are completely soluble, but the soluble nutrients in compost are still vulnerable to leaching in the event of a large rain event. Nitrogen (N) and phosphorus (P) are the limiting nutrients in the eutrophication process of aquatic ecosystems. Efforts to reduce anthropogenic sources of N and P to combat eutrophication and the proliferation of toxic algal blooms have proved successful. When incorporating large volumes of compost into soil, particularly manure-based composts, it is crucial to understand the physical, chemical and biological characteristics of the soil as well as the geographic and hydrologic qualities of the intended site. Once that site analysis is complete, a compost can be selected that fits the limitations of the site. If nutrient leaching is a concern and the remediation site displays one or more of the following characteristics:

- Soil texture is sandy, very well-drained
- Soil depth is shallow (<24inches)
- Site/soil is very wet, site is located in a wet climate, site is located at the bottom of a slope or amendment is being applied during a rainy season
- Slope of site is >4:1 (25%)
- Compost application is occurring more than one week before plant installation

the following modifications to the above specification are warranted. Limit composts to those with a C:N between 15:1 and 20:1 and a phosphorus content <0.5%. Consider using a compost that contains little to no animal manure. Additionally, consider using 25% compost by volume, instead of 33% compost by volume.

## REFERENCES:

Chatterjee, N.,Flury, M.,Hinman,C.,and Cogger,C.G.(2013).“Chemical and physical characteristics of compost leachates: A review.” ⟨http:// www.wsdot.wa.gov/research/reports/fullreports/819.1.pdf⟩

EPA (2012). Stormwater Best Management Practices: Compost Blankets. EPA 833-F-11-007. Retrieved from https://www3.epa.gov/npdes/pubs/compostblankets.pdf

Heyman, H (2019). Compost Quality Recommendations for Remediating Urban Soils. (Master’s Thesis). Cornell University, Ithaca, New York, USA.

Penn State Agricultural Analytical Services Lab (2019). Compost Sample Report. Retrieved from https://agsci.psu.edu/aasl/compost-testing

Reddy, N., & Crohn, D. M. (2012). Compost induced soil salinity: A new prediction method and its effect on plant growth. *Compost Science & Utilization*, *20*(3), 133-140. Retrieved from https://search-proquest-com.proxy.library.cornell.edu/docview/1082363646?accountid=10267

Risse, L.M. & Faucette, L.B. (2015). Compost Utilization for Erosion Control. *University of Georgia Extension.* Retrieved from https://extension.uga.edu/publications/detail.html?number=B1200&title=Compost%20Utilization%20for%20Erosion%20Control

Rivenshield, A., & Bassuk, N. (2007). Using organic amendments to decrease bulk density and increase macroporosity in compacted soils (Vol. 33).

Sax, M. S., Bassuk, N., van Es, H., & Rakow, D. (2017). Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. *Urban Forestry & Urban Greening*, *24*, 149–156. https://doi.org/10.1016/j.ufug.2017.03.023

Schwarz, M., & Bonhotal, J. (2017). Characteristics of a Sampling of New York State Composts. *Cornell Waste Management Institute.* Retrieved from https://ecommons.cornell.edu/handle/1813/48204.

Sikora, L. J., & Szmidt, R. A. (2001). Nitrogen sources, mineralization rates, and nitrogen nutrition benefits to plants from composts. *Compost utilization in horticultural cropping systems. CRC Press, Boca Raton, FL*, 287-305.

Sullivan, D. M., Bary, A. I., Miller, R. O., & Brewer, L. J. (n.d.). Interpreting Compost Analyses. *Oregon State University Extension Catalog.* Retrieved from file:///C:/Users/hfhey/Zotero/storage/ZUDKZZDQ/em9217.html.

Thompson, W., Leege, P., Millner, P., & Watson, M. E. (2002). Test methods for the examination of compost and composting (TMECC). *Reston, VA, USA: Composting Council*.

US Environmental Protection Agency (1997). *Part 503: Standard for the use or disposal of sewage sludge*, Chapter 40 Code of Federal Regulation: Environmental Protection Agency. The US Government Printing Office, pp: 422-500.

USCC. (2005). Landscape Architecture/Design Specifications for Compost Use. *United States Composting Council.* https://compostingcouncil.org/wp-content/plugins/wp-pdfupload/pdf/32/Landscape-Architecture-Specs.pdf